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Design of Canals

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Preface

Huge amounts of money are invested around the world in construction or upgradation of canals. Nearly 80–85 % of the cost of a total canal system constitutes transmission and the distribution canal networks. Due to the enormous costs involved, canal design is an area that has attracted many researchers for a long time.

The aim of this book is to provide the reader with an understanding of the analysis and design aspects of canals. The book covers the topics related to the analysis and design of water-carrying as well as sediment-transporting canals. It covers the uniform flow principles and their application in the determination of normal depth. The general principles of canal design have been covered to highlight the cost aspects and the other parameters required for the design of a canal. The other topics covered in the book relate to the determination of seepage discharge through canals of various shapes under different types of drainage positioning of drainage layers. The various topics pertain to canal design for minimum area, minimum earth work cost, minimum lining cost, minimum seepage loss, minimum evaporation loss, and their combinations. The design of contraction and expansive transitions is part of the design of cross drainage works. A chapter is also devoted to the design of these transitions.

Most of the designs are provided in a closed form that can be directly adopted by design engineers. A significant part of the book covers numerical examples. Experience has shown that complete mastery of the design project cannot be attained without familiarising oneself thoroughly with numerical procedures. For this reason, it is better not to consider numerical examples as a mere illustration but as an integral part of the general presentation.

The book is structured in a way so as to enable an engineer to design functionally efficient and least-cost canals. It is also intended to be useful for students, professional engineers, and researchers. Any suggestions for improvement of the book will be gratefully received.

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Authors' Biographic Sketch

Dr. P.K. Swamee is a distinguished Emeritus Professor of Civil Engineering at ITM University, Gurgaon, Haryana, India. He was formerly a Professor of Civil Engineering at the University of Roorkee (now the Indian Institute of Technology Roorkee), India. He has over fifty years of teaching, research, and industry experience in water resources engineering and has published numerous articles in international journals. Dr. Swamee is a Fellow of the Indian National Academy of Engineering.

Dr. B.R. Chahar is Professor of Civil Engineering at the Indian Institute of Technology Delhi, India. He was Visiting Professor at the Ecole des mines de Saint-Etienne, France, and Asian Institute of Technology, Bangkok. Dr. Chahar received his Ph.D. in Civil Engineering from IIT Roorkee and M.Tech. in Civil Engineering with specialisation in Water Resources Engineering from IIT Kharagpur. He has 22 years of teaching, research and industry experience in water resources engineering and has published numerous articles in reputed journals and proceedings. Dr. Chahar is a recipient of several scholarships and awards, including Visiting International Fellowship of EWRI of ASCE, Young Scientist of DST, and AICTE Career Award for Young Teachers. He is Fellow of ISH, IWWA, IE(I), and IWRS and life member of ISTE, IAH, and ASCE.

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Chapter 1
Introduction

Abstract Irrigation has been practiced since the beginning of civilization. A canal is used to convey water from a source to a destination for irrigation, industrial, or domestic use. The canal must be capable of transporting water between the source and the destination in a reliable and cost-effective manner. A brief history of developments in canals is presented. An outline of all chapters and scope of the book are also reported in the chapter.

Keywords Irrigation • Canal • Uniform flow • Resistance equation • Seepage loss • Canal lining • Canal alignment • Section cost

1.1 General

A canal is used to convey water from a source to a destination for irrigation, industrial or domestic use. The canal must be capable of transporting water between the source and the destination in a safe and cost-effective manner.

Irrigation has been practiced since the beginning of civilization. In due course of time, it was discovered that water could be diverted from a stream and conveyed under gravity flow in a ditch to a lower land. The large-scale diversion of water for irrigation was established in historic times in Mesopotamia 5,000–6,000 years ago (Butler 1960). The Sumerians developed extensive and intricate networks of irrigation channels around 3,000 B.C. Some of the canals still exist in usable form, e.g., Shatt-al Hai canal in Iraq built around the middle of the third millennium B.C. (Lewis 1960). Historical developments in irrigation canals are reported by Framji et al. (1982) for the period starting from the old civilizations in India, China, Egypt, etc., to the post-Christ period in all over the world.

During the latter half of nineteenth century, investigators worked towards the rational design of irrigation canals. Kennedy (1895), Lindley (1919), Lacey (1930, 1940, 1946), and others developed the regime equations for design of stable channels. The stable channel design by limiting tractive force approach was originated by Lane (1937, 1955) and others. Framji (1972) has outlined design methods for irrigation canals practiced in different countries.

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As the slope required for irrigation canals is much less than the ground slope, falls are provided to save the earthwork in filling cost. These falls are utilized in power generation. On the other hand, canals are exclusively constructed for power generation. Run-of-the-river hydropower channel is one such example in which very little storage is required. In both run-of-the-river and storage schemes of hydropower generation, water is diverted from one point on the river to the turbines and then from turbine house back to the river.

Ship canals or enlarged barge canals are constructed to accommodate ships. As ship canals are not supposed to carry any discharge, the dimensions for ship canals are largely governed by the size of the largest ships the canal is supposed to carry. Ship canals may be constructed to create a shortcut for avoiding lengthy detours, to create a shipping route between two land-locked seas or lakes, to provide inland cities with a direct shipping link to the sea, etc.

1.2 Objective Function

The optimal design of a canal consists of minimization of an objective function which is subjected to certain constraints. The known parameters are flow discharge, longitudinal bed slope of canal, and the canal surface roughness. There are various objective functions such as flow area, earthwork cost, lining cost, seepage loss, evaporation loss, and their combinations (Swamee et al. 2000a, b, c, 2001a, b, 2002a, b; Chahar 2000; Basu 2013). Apart from costs, reliability is another important objective of the canal design. However, there has been no attempt in this direction.

As artificial channels have objective function, natural channels also have objectives. A natural channel is a stream in equilibrium, which is neither silting nor scouring over a period of time. Obviously, such a stream has developed a cross-sectional area of flow through natural processes of deposition and scour. Using Lacey's equations for stable channel geometry, and using geometric programming, Swamee (2000) synthesized an objective function for stable alluvial channels. On the other hand, in a similar manner, Swamee et al. (2008) found an objective function for river Brahmaputra. Chapter 2 formulates objective functions.

1.3 Uniform Flow

Canals are designed for uniform flow considering economy and reliability. Uniform flow is described by a resistance equation. Whereas the economy is achieved by minimization of cost, maximum reliability is realized by delivery of discharge with the least frequency of failures.

The first uniform flow equation was derived by Antoine de Chézy (Rouse and Ince 1963) in 1769 mathematically from the definition of uniform flow with the assumption that the force resisting the flow per unit area of the stream bed is proportional to the square of the velocity. Other commonly used equations are due to Ganguillet and Kutter and Manning. Though the Ganguillet and Kutter equation appears cumbersome, it became the most popular equation of its time, and many tables and charts (Garrett 1948) were prepared for its use. The popularly known Manning's equation was proposed by Gauckler (Williams 1970; Rouse 1956) in 1867 and Hagen in 1876; Hagen obtained the same relationship using Upper Ganga Canal data, which were collected by Cunningham with observations at Roorkee (Mital 1986). Later, Vallot in 1887 and Thrupp in 1888 (Williams 1970) also obtained the same equation. For high roughness projections and for high enough Reynolds numbers, friction is independent of Reynolds number and depends only on the hydraulic radius of the flow for a given type of channel surface, and hence, Manning's equation is applicable only to the fully rough turbulent flow and in a limited bandwidth of relative roughness (Christensen 1984). For other flow conditions, the Colebrook equation is more appropriate than the Manning's equation ("Friction" 1963). A more general resistance equation based on roughness height was given by Swamee (1994). Chapter 3 describes uniform flow equations for viscous flow, turbulent flow, and sediment-transporting channels.

1.4 General Principles

In designing canals, various factors are considered, for example, the kind of material forming the channel surface which determines the roughness coefficient, the minimum permissible velocity to avoid deposition of silt or debris, the limiting velocity to avoid erosion of the channel surface, and the topography of the channel route which fixes the channel bed slope. Chapter 4 describes general principles of canal design, which includes essential input parameters and safety and system constraints.

1.5 Minimum Area Section

A canal based on minimization of flow area objective function is also a maximum velocity canal. Several literature is available on minimum area section (Chahar 2005, 2007), but majority of literature used Manning's equation while only few (Chahar 2000; Swamee 1995) have used general resistance equation in design of such sections. Design of minimum flow area section has been covered in Chap. 5.

1.6 Minimum Cost Canal Section

Design of a minimum cost canal section involves minimization of the sum of earthwork cost and cost of lining subject to uniform flow condition in the canal (Swamee et al. 2000b, 2001a). In general, the cost of earthwork varies with canal depth. Chapter 6 discusses the optimization method to obtain minimum cost canal sections.

1.7 Minimum Water Loss Section

An irrigation canal may be an unlined canal or a lined canal. The loss of water due to seepage and evaporation from canals constitutes a substantial part of the available water. By the time the water reaches the field, up to one-half of the water supplied at the head of the canal may be lost in transit (Sharma and Chawla 1975). The evaporation loss is important particularly for a long channel carrying a small discharge in water-scarce areas of arid regions. The seepage loss from canals depends on hydraulic conductivity of the subsoils, canal geometry, and location of water table relative to the canal. The seepage loss results not only in depleted fresh water resources but also causes water logging, salinization, groundwater contamination, and health hazards. Canal lining checks the seepage from a canal. To minimize seepage and to transport water efficiently, lined canals were envisaged. Nowadays, a new canal, preferably, is constructed as a lined canal. A perfect lining would prevent all the seepage loss, but canal lining deteriorates with time. An examination of canals by Wachyan and Rushton (1987) indicates that even with the greatest care, the lining does not remain perfect. A well-maintained canal with 99 % perfect lining reduces seepage about 30–40 % (Wachyan and Rushton 1987). Cracks in canal lining develop due to settlement of the subgrade, weed growth in the canal, construction defects, use of inferior-quality lining materials, weathering, etc. The thickness of the lining material is small and cracks may develop anywhere on the perimeter. Therefore, seepage from a canal with cracked lining is likely to approach the quantity of seepage from an unlined canal. Chapter 7 deals with the design of canal sections considering seepage and evaporation water losses as reported by Swamee et al. (2000a, 2001b, 2002a).

1.8 Minimum Overall Cost Section

Design of a minimum cost canal section involves minimization of the sum of earthwork cost, cost of lining, and cost of water lost as seepage and evaporation subject to uniform flow condition in the canal. Swamee et al. (2000c) took into account all such costs in the design of minimum cost canal sections. The optimal canal design equations considering overall cost due to lining, earthwork, and water loss are highlighted in Chap. 8.

1.9 Canal Transitions

A canal from source to destination may be of several hundred kilometers. The discharge in the canal varies along the length due to diversion and losses; therefore, a reduced canal section matching with the discharge is adopted. Canal section may also change at flumes, siphons, and aqueducts. A canal transition involving an expansion or contraction of the section is required whenever there is change in the canal section. A transition is a structure of short length; thus, the cost aspect of transitions is not considered in their design. Chapter 9 gives design procedure for both contraction and expansion transitions.

1.10 Transmission Canal

A transmission canal conveys water from the source to a distribution canal. Many times, the area to be irrigated lies very far from the source, requiring long transmission canals. Though there is no withdrawal from a transmission canal, it loses water on account of seepage and evaporation. Hence, it is not economical to continue the same section throughout the length of a long transmission canal. Instead a transmission canal should be divided into subsections or reaches, and the cross section for each of the subsections must be designed separately (Swamee et al. 2002b). This would result in reduced cross sections in the subsequent reaches. The reduced cross section not only results in cost saving for earthwork, lining, and water lost but also requires less cost in land acquisition, construction of bridges, and cross-drainage works. Chapter 10 addresses the problem of design of transmission canal.

1.11 Canal Route Alignment

The total cost of a canal project depends upon the alignment. The alignment is the feasible path or route from a source location to the desired destination. A canal has to be aligned in such a way that it covers the entire area proposed to be irrigated with the shortest possible length, and at the same time, its cost including the cost of cross-drainage works is a minimum. A shorter length of canal ensures less loss of head due to friction and smaller loss of discharge due to seepage and evaporation, so that additional areas can be brought under cultivation. Canal alignment may be contour canal, side slope canal, or ridge canal as per terrain of command area. A contour canal irrigates only one side of the canal and it crosses a number of valleys; thus, it involves different types of cross-drainage works such as aqueducts, under tunnels, super passages, etc. A side slope canal is aligned at right angles to the contours of a country. A watershed or ridge canal irrigates the areas on both sides. Cross-drainage works are completely eliminated in watershed and side slope canals. The main canal is generally carried on a contour alignment, until either it commands the full area to be irrigated or it attains the top of a watershed to become a watershed canal thereafter. Branch canals and distributaries take off from a canal from or near the points where the canal crosses the watershed. The alignment of a canal is decided after a careful consideration of the economy. Several alignments between the source and the destination may be possible. An alignment mainly depends on the topography. Out of many alignments, few may not be feasible to construct due to construction-related problems. Canals are aligned as far as possible in partial cutting and partial filling. Deep cutting or high embankments are generally avoided by suitable detouring after comparing the overall costs of the alternative alignments. Land cost varies with land use pattern, resettlement, and rehabilitation cost, environmental cost, and alignment of the canal; the cost of canal falls/drops/cross-drainage works varies with the type and size of structure. The maximization of economy is achievable by minimization of the total cost of canal route alignment considering all possible cost factors (Basu 2013; Swamee and Chahar 2013). This type of canal alignment problem is solved in Chap. 11.

1.12 Mathematical Terms

- Adjoint variables: The undetermined multipliers used in formation of Hamiltonian are called the adjoint variables. In the present case, these variables are functions of space.
- Design variables: These are the variables that are determined in a design process.
- Grid search method: This is a method of optimization in which the values of objective function $F(x_1, x_2, \ldots x_n)$ are computed at equispaced points in the domain of variables $x_1, x_2, \ldots x_n$, and the optimum is found by comparing these values. The process is repeated in the neighborhood of the located optima till desired accuracy is achieved. Thus, it is a brute force method of optimization.
- Hamiltonian: This is a function formed by adding the integrand of the objective functional with the state equations through undetermined multipliers.
- Objective function: It is a function expressing the requirements of an engineering system like cost, efficiency, and power consumption. When this function is optimized (minimized or maximized), it yields the best engineering design.
- Optimal control problem: In this problem the objective function is in the form of an integral (called functional) involving the design variable as an unknown function of space along with state variables. The restrictions imposed on state variables and the design variables are in the form of differential equations. The original problem as formulated in electrical engineering is in time domain. In this paper, it is converted in space domain.