AQUEDUCTS, TUNNELS, CANALS, PIPELINES, SIPHONS, AND WATER DISTRIBUTION

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Summary

Aqueducts have been used for thousands of years to transfer water long distances for public water supply. Ancient structures were open channels, but nowadays they may consist of tunnels, canals, pipelines, and siphons or any combination of these.

Tunnels are used for transporting trains, automobiles, water, storm and sanitary flows, pedestrians, bicycles, and no doubt other items. Large ones are sometimes used for

temporary storage of storm water.

Canals are the cheapest means for transporting water, but they are not protected from contamination or losses by leakage and evaporation, and they must follow a falling gradient intersection with the ground surface.
Pipelines are protected from contamination and evaporation, and, as they are pressurized, they can follow rising and falling profiles. Pipes, valves, and fittings are made of a wide variety of materials.

Two types of siphon designs have been used for both water and wastewater systems: head recovery siphons and inverted siphons. Head recovery siphons are true siphons, but inverted siphons are technically not siphons at all. Instead, they are pressure pipelines designed to transport the fluid by gravity across obstacles such as valleys and under obstructions such as highways, railways, and bodies of water.

Water distribution systems are the final step between the water source and the customer. They follow water treatment and furnish almost 100 per cent protection provided the system is always under pressure and contains a residual of a disinfectant such as chlorine or chlorine dioxide to guard against contamination from cross-connections or repairs.

1. Aqueducts

Aqueducts have been used for several millennia. Stone collars for what was probably wood pipe have been excavated in ancient Sumeria, but Rome is the first city to install aqueducts on a grand scale. Their first was a 16 km underground aqueduct built in 310 BC. The first aqueduct above ground was 145 km long built in 144 BC. Eventually, more than 10 aqueducts carried a total of 1.6 $m^3\ s^{-1}$ of high-quality water to the fastidious Romans. These stone structures were usually open conduits with relatively flat slopes for gravity flow, so the flow depended only on the slope and size of the conduit. A small gate was used to control the release of water into the conduit. Some, still in use, supply water for the fountains of Rome. Two examples of more modern aqueducts constructed for water supply to New York City include the Old Croton Aqueduct and the New Croton Aqueduct.

1.1 Introduction

Modern water supply aqueducts include open channel canals, tunnels, siphons, and pipelines. These structures may be combined in any manner to carry water for long distances to holding reservoirs or water treatment plants for distribution to the water consumers. The largest aqueduct in the world supplies southern California with nearly 44 $m^3\ s^{-1}$ of water carried in open concrete-lined canals from the Colorado River. The aqueducts used to supply water to New York City are tunnels and vary from 53 to 148 km in length. Both systems withdraw water from storage reservoirs formed by large dams.

1.2 Examples

The first major tunnel aqueduct in the United States was called the Old Croton Aqueduct (OCA) and completed in 1842 from the Croton River to New York City. A cyclopean masonry dam 14 m high was constructed across the Croton River to form a reservoir for water storage. An intake structure was constructed in the dam to transmit water to the aqueduct. The OCA was excavated in overburden materials, so the route was subject to the geography of the land and the location of bedrock along the route thus making the alignment circuitous. The aqueduct was lined with several courses of brick and mortar to reduce seepage. The OCA was 65 km long, carried a normal flow of about $3.5 m^3/s$, and required 5 years for construction. A bridge to support the aqueduct was built across the Harlem River, a major obstacle. The gradient of 0.00014 allowed the aqueduct to transmit the entire flow by gravity from the storage reservoir to the city. The aqueduct was in use for 116 years.

A second aqueduct, called the New Croton Aqueduct (NCA), was built in 1895 to increase the capacity of the water supply to the City (See Figure 1). It was a tunnel with more direct alignment, very few curves, and shorter than the OCA by about 11 km. Two inverted siphons carried water below deep overburden deposits within the rock foundation at one location and the Harlem River at the other location. The NCA has a 40-km gravity flow section and a 13-km pressurized flow section. This aqueduct, also lined with several courses of brick and mortar to reduce seepage, was laid on a relatively flat slope of 0.00014, and it delivered about 13 $m^3 s^{-1}$ by gravity flow from a new, larger reservoir in the Croton River 5 km downstream from the older dam. This 105-year old aqueduct is still operated for water supply today.

Figure 1: New Croton Aqueduct, a 4.27-m horseshoe-shaped tunnel.
Courtesy of Harza Engineering Co., Chicago, IL, USA

2. Tunnels

Tunnels can be excavated in everything from stable to unstable rock or unstable soils. Geologic studies and site explorations, performed prior to tunnel excavation, provide information for design and construction methods.

2.1 Introduction

Tunnels are excavated using (1) drilling and blasting, (2) tunnel boring machines, (3) earth pressure boring shields, or (4) heavy hydraulic hammers. Many tunnels are lined using concrete, decorative concrete liners, steel, shotcrete, plastic and fiberglass. Some tunnels are left unlined. All tunnels require some form of permanent support after tunnel excavation to stabilize the native materials and prevent their fall into the tunnel.

2.2 Geologic Studies and Exploration

Before proceeding with the final design or construction of a tunnel, a program of geologic studies and exploration is required to determine the geology and physical properties of the soil and rock materials through which the tunnel is to be driven. The geologic studies are required to determine the rock types and locations of potential faults and geologic anomalies that may affect the details of constructing the tunnel. Geologic maps, soil conservation service maps, and other information available from local, state and national records are used for these studies.

The exploration program consists of drilling holes through these materials, recovering samples, and performing tests on the samples to document the properties. An experienced geologist usually logs all holes to document the rock jointing, and its orientation and frequency. Water pressure tests are also performed to determine the permeability of the jointing within the rock mass. The number of holes drilled varies depending on the type of rock, geography, and results of the geologic and preliminary design studies performed prior to start of final design. Rock core sample testing may include density, unconfined compression, modulus of elasticity, and occasionally other properties. Soils are tested to determine soil classification, density, strength, permeability, and compressibility.

2.3 Excavation

Tunnels are excavated either from portals or from shafts. Portals are common for transportation tunnels excavated through hills or mountains. Tunnels for community water supply, hydroelectric plants, or for storm water often require shafts for access to construct the tunnel, to remove tunnel muck, to transmit raw, finished, or storm water to the tunnels, or for ventilation. Shafts are usually vertical and excavated by drilling and blasting or by raise boring.

Drilling and blasting consists of drilling blast holes 38 mm in diameter to a depth slightly deeper than the desired rock excavation for a single round. The holes are then loaded with modern blasting material and sand. The blasting material in the holes is then ignited to loosen the rock so that it can be efficiently excavated. Blasting is controlled to minimize the particle velocity and air over-pressure to prevent damage to surrounding structures. Seismographs are used to measure the vibrations induced in the ground by the blasting. Typically blast vibrations that may reach adjacent structures are controlled within a range of 0.2 to 0.6 m s^{-1}**.** Air blast overpressure and impact noise are also typically limited to 115 dB and measured with an impact noise meter or a nearby seismograph.

Techniques used to move the rock for easy excavation include the following:

- Drilling holes at a proper spacing for the depth of the round,
- Loading the holes with the proper amount of blasting materials so that the rock is loosened, broken and moved but not shattered,
- Placing most of the blasting material at the bottom third of the blast hole to move the rock mass toward the open face,
- Use of pre-splitting methods where the holes that define the limits of the area to be excavated are shot milliseconds before the bulk of the blasting materials so that a relatively smooth blast line is developed, and
- Use of millisecond delays during ignition to move the center of the rock mass before the sides so that the rock mass bulks up and into the open face.

Raise boring can only be performed if a tunnel exists below a proposed shaft. The method consists of drilling a small hole from the top of the proposed shaft to the tunnel below. A drill shaft is then placed in the small drilled hole with a cutter head attached to the bottom of the drill shaft. A drillmotor is then attached to the drill shaft at the top of the proposed shaft and the shaft is then drilled from the bottom up to the top. The cuttings from the drilling fall into the tunnel from which they are easily removed. Shafts can also be down drilled, but in this operation the drill cuttings must be removed from the top of the shaft.

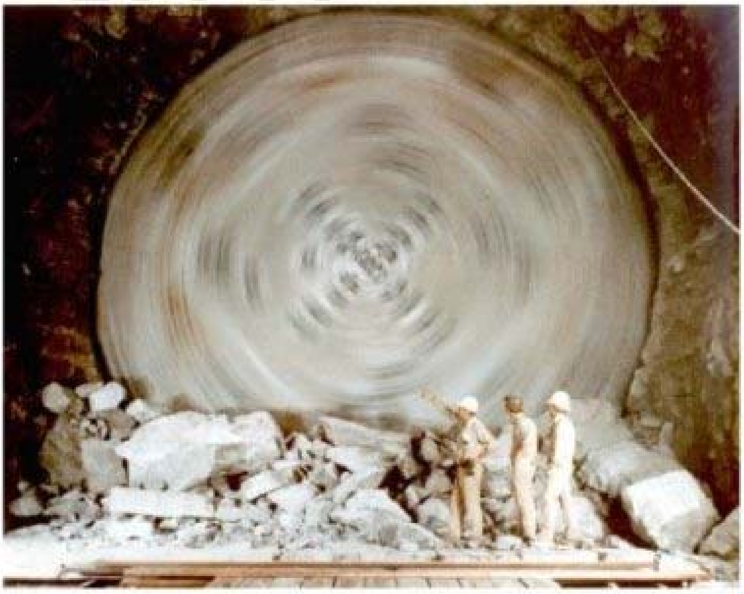

Figure 2: Chicago Tunnel and Reservoir Plan (TARP) 9.76-m diameter Tunnel Boring Machine. *Courtesy of Harza Engineering Co., Chicago, IL.*

Tunnels in rock can be excavated by use of drill and blast techniques or by tunnel boring machines (TBMs). TBMs have cutter heads driven by powerful motors that continuously cut the rock efficiently by the use of bits on the face of the drill head (See Figures 2 and 3). The rock cuttings (tunnel muck) are removed behind the TBM by conveyors to the shaft or by means of small railroad cars that carry the tunnel muck to the shaft for removal to the surface. Tunnel boring machines are economical only for tunnel lengths of more than 1 km. Shorter lengths have been excavated by TBMs under unusual circumstances. Micro TBMs have also been used to excavate small diameter tunnels in rock or soil materials for installation of cables, small sewer conduits or water and storm sewer lines. TBMs have been used to excavate tunnels up to 15 m in diameter and larger machines are being designed. Almost all of the 120-km of storm sewer tunnels in the limestone below the City of Chicago have been excavated by TBMs. Advance rates for the TBMs range from 150 to 400 feet per day depending on the rock geology and other factors.

Regardless of the method of excavation, all tunnels require some support to stabilize the rock and prevent rock falls into the tunnel after excavation. Rock bolts, shotcrete, steel ribs and lagging, and liner plates are the devices used to support the rock and soil surface after excavation. These supports are permanent and maintain stable rock faces during the life of the tunnel.

2.4 Lining

Tunnels are lined to prevent exfiltration out of or infiltration into the tunnel and to provide a smooth surface for improved hydraulic flow. But not all tunnels are lined. Some tunnels for raw water supply or for hydroelectric plants are excavated, supported, and allowed to operate unlined.

Figure 3: Typical side view of a tunnel boring machine.
Courtesy of Harza Engineering Co., Chicago, IL, USA.

Although linings may be concrete pipe, steel plate or pipe, and plastic or fiberglass pipe, the most common lining material is cast-in-place concrete. Steel linings are normally used when high internal water pressures are expected. The thickness of concrete lining is normally at least 300 mm and may even be 1000 mm for some applications. The thickness of steel pipe depends on the internal and external water pressures. Some tunnels under high internal pressures (several hundred kPa) have steel linings 25 to 50 mm or more in thickness. When lower pressures are anticipated, thicknesses of 6 to 18 mm are more common. Some tunnels have also been lined with a thin (100 mm more or less) layer of shotcrete for protection against rock deterioration. Transportation tunnels are usually lined with decorative precast concrete liners.

3. Canals

Many civilizations throughout history have developed at or near ample supplies of rivers and lakes to satisfy the need for water for domestic use, transportation of people and goods, and irrigation. Ancient examples include the Indus River in India and the Nile River in Egypt.

3.1 Introduction

Over time, population centers grew in regions at some distance from adequate fresh water supplies, and the need to convey water became apparent. Ancient civilizations soon learned the rudiments of the construction of canals, which are channels cut into the earth that allow for the routing of water down slope in much the same way as a river flows.

As population centers prospered and grew during the Industrial Revolution, the spread of disease from the pollution of nearby water supplies gave renewed impetus to the importation of water from more pristine sources. New York City, for example, imported water from the upstate region of the Catskill Mountains to satisfy the need for drinking water in the late nineteenth century.

The development of hydrodynamic (kinetic) pumps and the electrical motors to drive them and the increasingly widespread availability of electrical power during the nineteenth and twentieth centuries have made the pressurization and distribution of water through pipelines much more common, even allowing for water to be sent uphill. Although pipelines are more expensive than canals, they avoid the major drawbacks associated with canals: ease of pollution, flooding during heavy rainfall, loss of water through leakage and evaporation, high maintenance, and even drownings.

Nevertheless, the absence of a power requirement for the transmission of water in canals makes them an important option for consideration whether for very remote areas without electrical power, or for the routing of large volumes of water. Los Angeles, for example, imports Colorado River water hundreds of miles through canals to satisfy a significant portion of its water needs. Canals are the most common conveyance system for transporting irrigation water. The construction of a canal for the transmission of a water supply involves the determination of a route, the channel cross section, and the choice of control structures to regulate the flow.

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Biographical Sketches

W. James Marold, P.E., obtained a Bachelors of Science Degree in Civil Engineering from the University of Notre Dame in 1965 and a Masters of Science Degree in Civil Engineering from the

University of Notre Dame in 1969. He is a professional registered engineer in Illinois and Ohio. He is a member of the American Society of Civil Engineers, American Society of Testing Materials, Chi Epsilon, and Association of State Dam Safety Officials.

He is the Manager of Site Development Sub-Unit in the Energy and Infrastructure Business Unitand is a partner in the firm of Montgomery Watson Harza (MWH). He has worked in the former firm of Harza Enginnering Company and MWH for 35 years.

Mr. Marold has served as project manager, senior civil design and construction engineer, and as lead geotechnical engineer on infrastructure projects consisting of lakeshore and river restoration, locks, tunnels, storm sewers, marinas and boat launch projects. He has also been involved in dam inspection, dam rehabilitation, water supply, and hydroelectric projects. He has supervised or performed exploration programs, design studies or served as resident engineer for storm water drainage and concrete pump-station structures, industrial waste disposal facilities, highways and railroads, earth, rockfill, and concrete gravity dams, pumped-storage plants; and the rehabilitation of several dams. He has been responsible for projects from feasibility and exploration through design and completion of construction.

He is the author of 9 technical papers and has been a member of the American Society of Civil Engineers Hydropower Committee, the Task Committee on Inspection & Monitoring of In-Service Penstocks and the Task Committee on Guidelines for Inspection and Evaluation of Existing Water Control Gates.

He was awarded in 1999, along with all the task committee members, the prestigious Rickey Medal for the guideline publications on “Guidelines for Evaluating Aging Penstocks” published by ASCE in 1995 and “Guidelines for Inspection and Monitoring of In-Service Penstocks” published in 1998.

He has also taken several foreign assignments for periods of one month to 5 years in Belize, El Salvador, India, Venezuela, and Honduras. He is reasonably fluent in Spanish.

Robert Lang, Ph.D., P.E., has been teaching civil and environmental engineering for over ten years. Previously, he had been the chief civil engineer for an irrigation district in Southern California that contains several thousand kilometers of irrigation canals, rivers, and drain channels. His last major project there was to oversee and extensive water conservation program that involved the re-design of man canals, and the design and construction of several regulating reservoirs. To assess the impact of the water conservation program on the Salton Sea, which ultimately receives all drainage water from the district, he developed a hydrologic and water quality model. For his doctoral dissertation, he dev eloped a finite element contaminant transport model to predict the movement of trace organic gasses in municipal solid waste landfills.

Bayard E. Bosserman II, P.E. serves as a Principal Engineer with Boyle Engineering Corporation in Newport Beach, California, USA. He is a registered professional engineer in five states in the United States. He has a Bachelor’s degree (1972) with a triple major in mathematics, physics, and economics from Cornell College and a Master’s degree (1973) in civil engineering from Stanford University.

He specializes in the design of water and wastewater pumping facilities and in analyzing fluid mechanics and hydraulic transient problems in pumping stations, piping, and control valves. His expertise in facilities design includes establishing design criteria; selecting and specifying piping, valves, and mechanical equipment; and selecting and specifying materials and coatings for corrosion control in process equipment, piping, and valves.

He co-authored the book *Pumping Station Design* published in 1989 (first edition) and 1998 (second edition) and which was selected by the Association of American Publishers as the “Most Outstanding Engineering Text.” He served as the principal author of five chapters, including the chapters on piping, valves, water pumping station design, and the two chapters on analysis and control of hydraulic transients (surge). He also served as the principal author of the chapter on “Pump Systems Hydraulic Design,” published in the McGraw-Hill handbooks *Water Distribution System Handbook* (1999) and *Hydraulic Design Handbook* (2000). He has published more than 15 articles on hydraulic transient analysis and pumping station design.

Mr. Bosserman has served as project manager or project engineer for more than 100 pumping stations and flow control facilities within his 30 year career. Pumping stations have ranged from 10 to15,000 kilowatts and up to 1,100 million liters per day capacity. Flow control facilities have ranged up to 1,800 million liters per day. Piping and valve sizes have ranged up to 2,900 millimeters, with pressures up to 3,100 kilopascals.

He is a member of several professional societies and is active in several professional standards committees. He is a diplomate of the American Academy of Environmental Engineers; a member of the American Water Works Association; a member of the American Institute for the Advancement of Engineering; and a member of the American Society of Civil Engineers. He is the Chair of two technical standards committees in the American Water Works Association.

Garr M. Jones, P.E., Mr. Jones is Senior Vice President, Design for Brown and Caldwell, Consulting Engineers, San Diego, California, USA. He has been involved in virtually all aspects of design of water and wastewater collection, distribution, treatment and disposal. Mr. Jones has Bachelor of Science degrees in Civil Engineering and Industrial Engineering from the University of Washington and holds Life Memberships in the Water Environment Federation, the American Society of Civil Engineers and the American Water Works Association. He is currently serving as chair for Committee 820 (Wastewater Facilities) for the National Fire Protection Association. Mr. Jones participated in the development of ANSI/HI 9.8 (Pump Intakes) and the AWWA standards for Weirs and Scum Baffles and Wash Water Troughs. Mr. Jones is licensed to practice engineering in 30 states in the United States of America and the Province of British Columbia. Mr. Jones served as a co-editor for the publication *Pumping Station Design*, First and Second editions, Butterworth Heinemann, and has authored 12 papers on various subjects dealing with water and wastewater applications.

Thomas M. Walski, Ph.D., P.E., is Vice President of Engineering for Haestad Methods, Inc. of Waterbury, Conn., USA. He has served as executive director for the Wyoming Valley Sanitary Authority (regional wastewater system), engineering manager for Pennsylvania American Water Company (large regional water company) and associate professor of Environmental Engineering at Wilkes University (Wilkes-Barre, PA). His work has focused on applying state-of-the-art hydraulic modeling techniques to solve real world problems. He is author of over 100 papers and several books, most recently *Water Distribution Modeling* with Don Chase and Dragan Savic. He frequently teaches short courses on modeling to practicing engineers and is former editor of the *Journal of Environmental Engineering*.