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Operation and Maintenance of Hydraulic Structures

Musa Abubakar Tadda, Amimul Ahsan, Monzur Imteaz, Abubakar Shitu, Umar Abdulkaki Danhassan and Aliyu Idris Muhammad

Abstract

Water is among the most valuable resources that nature has endowed to human beings. Water has cut across all spans of life from cradle to grave. Since time immemorial, man continuously developed methods and techniques to harness the benefits of water and as well to protect himself from the destruction that may be caused by the same water. Therefore, for a hydraulic structure to answer its name, it must be capable of being used smoothly for the purposes it was designed for and also be able to be controlled effectively without the risk of causing any havoc to the environment. Using water, especially for agricultural purposes, cannot be overemphasized. Hence, this chapter discusses the hydraulic structures based on the work they performed, challenges facing hydraulic structures, and management procedures of the hydraulic structures in order to adequately and efficiently serve their purpose.

Keywords: hydraulic structures, operation, maintenance, water, design

1. Introduction

Hydraulic structures play an important role in drainage, irrigation, and hydraulic projects. If hydraulic structures fail, it may cause serious damages of wealth, properties, and environment as well as losses of life and injury to economy. The water related infrastructures are constructed at the aims to facilitate human needs/desires and enhance the quality of life such as drainage channel, river/channel, irrigation canal, bank/foot protection work, embankment, dam, spur dike/groyne, bridge/culvert, regulator, barrage/large regulator, aqueduct, pump station, siphon, and sluice. The details of some of the hydraulic structures are presented below.

1.1 Types of hydraulic structures

Hydraulic structures are structures that are fully or partially submerged in water. The essence of building hydraulic structures is to either divert, disrupt, store, or completely stop the natural flow of water bodies. Based on the work they are designed to perform on streamflow, hydraulic structures are categorized as water-retaining structures (dams and barrages), water-conveying structures (artificial channels), and special-purpose structures (structures for hydropower generation or inland waterways) [1].

1.1.1 Water-retaining structures

The dam is an essential hydraulic structure that all other structures directly or indirectly relied upon. Dams and barrages are typical *water-retaining structures* that are built purposely to impound water. The retained water behind dams and barrages could be used for other purposes such as irrigation, recreational activities, navigation, and a lot more. As of September 2019, there are 57,985 registered dams in the world [2]. Regardless of their size and type, dams demonstrate high complexity in their load response and interactive relationship with site hydrology and geology. Dams are of different sizes and shapes and made of various materials such as soil or rockfill embankment, mass concrete, reinforced concrete, masonry, and wood. However, based on the construction materials used, dams are broadly classified into concrete dams and embankment dams.

- Concrete dams comprised of gravity (PG), arch (VA), buttress (CB), barrage (BM), and multiple-arch dams (MV) as shown in **Figure 1a–e**. All these dams are constructed of mass concrete and sometimes of masonry with appropriate structural quality [1, 2]. Recent statistics show that concrete dams occupied only 20–22%, while embankment dams accounted for 78–80%.
- Embankment dams are of two types, earthfill (TE) and rockfill (ER), both of which are constructed by mass filling of naturally existing ground materials (soil and rocks). The construction materials are graded and well compacted to resist seepage and sliding. Embankment dams are characterized by having similar moderate face slopes at both upstream and downstream. This feature gives rise to a broad trapezoidal cross section and a high construction volume, which is relative to the dams' height that can cover >300 m [2].

1.1.2 Water-conveying structures

Any artificial facility cut in the ground with the sole purpose of transporting water diverted from main sources (river and dams) is termed as the *water-conveying structure*. These types of structures are comprised of canals (**Figure 2a**) and tunnels (**Figure 2b**) (usually made from soil and rocks) or siphons, aqueducts (**Figure 2c**), flumes (**Figure 2d**), and pipelines (usually made from concrete and metals) [1]. Before the construction of any water-conveying structure, a detailed geotechnical soil test and analysis is recommended to avail the surface and subsurface properties of the soil on which the structure is upon rest. The same soil test and analysis also applies to other types and classes of hydraulic structures to ensure safety and to save resources.

1.1.3 Special-purpose hydraulic structures

As the name implies, *special-purpose hydraulic structures* are built as an integral part of hydraulic project to meet a special purpose such as hydropower generation (e.g., surge towers and shafts, forebays, and head ponds), navigation (e.g., landings, berths, substations for ship repair, etc.), fishing (e.g., fish nursery ponds, fish lifts and locks, fishways, etc.), water supply for domestic and industrial uses (e.g., water intakes to treatment plant, pumping stations, etc.), waste disposal/sewage (e.g., sewage headers, pumping stations, channels after treatment plant to water bodies, etc.), and land reclamation (e.g., irrigation canals, drainage systems, silt tanks, etc.) [1, 7].

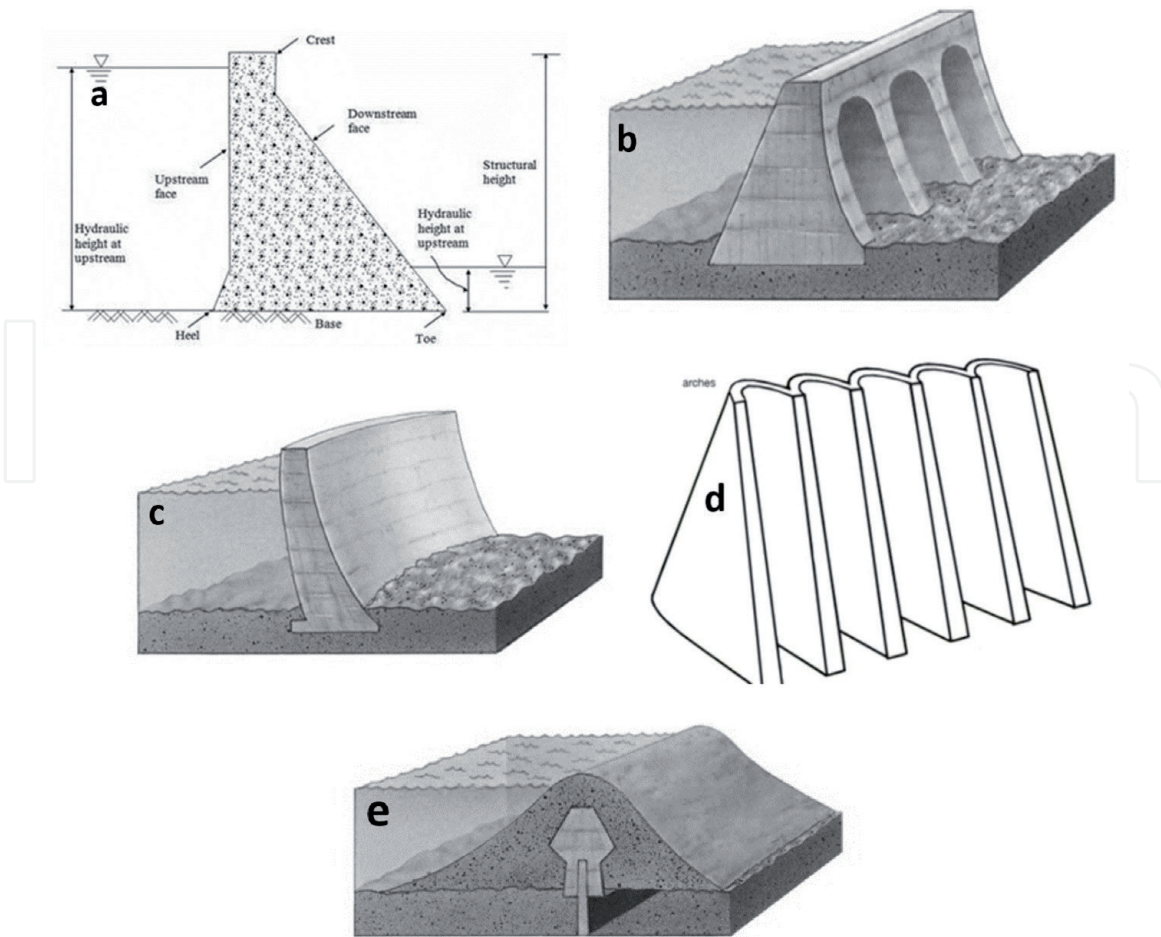


Figure 1.
 (a) Gravity dam, (b) arch dam, (c) buttress dam, (d) multiple-arch dam, (e) earthfill and rockfill dam.
 Source: [3].

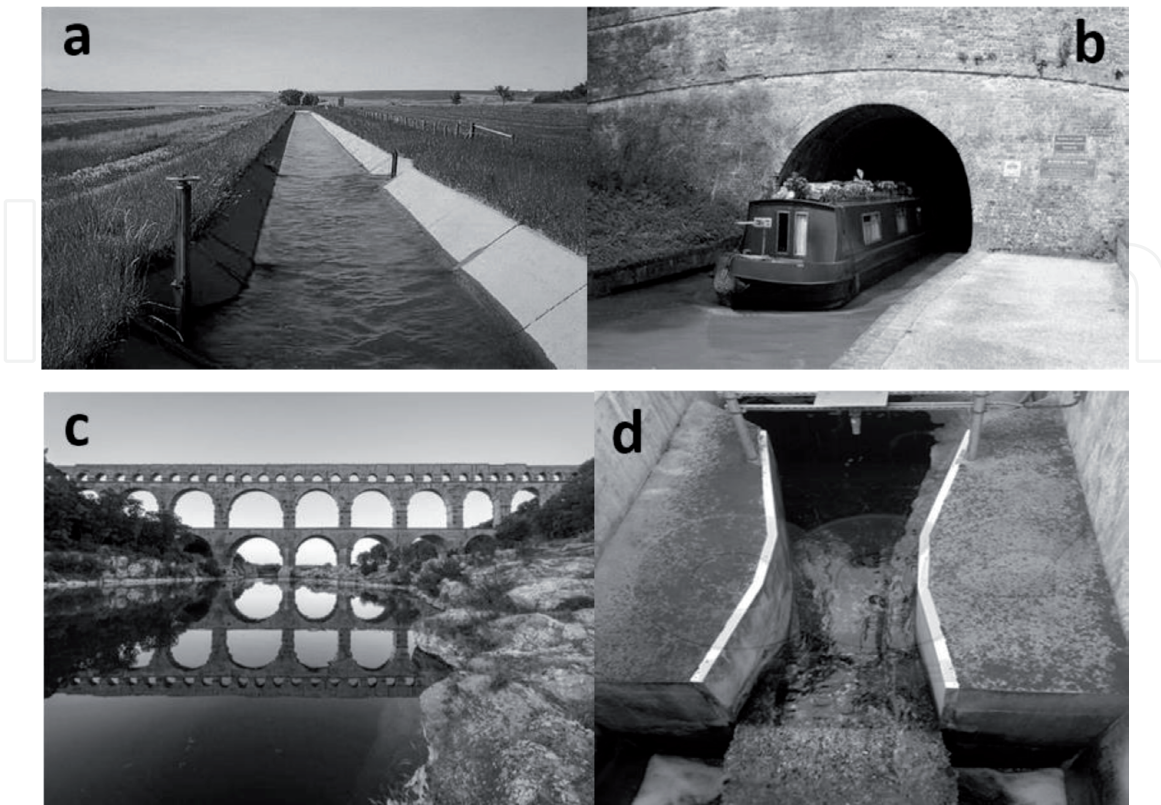


Figure 2.
 (a) Canals, (b) tunnels, (c) aqueducts, and (d) flumes. Source: [4–6].

2. Purposes of hydraulic structures

Hydraulic structures are purposely for managing and controlling the flow of water in natural and built environment systems. Moreover, the primary purposes may include the following flood control, water conveyance, irrigation, navigation, power generation, domestic and industrial purposes, environment protection, and recreation, among others.

2.1 Flood control

Flooding is a geophysical hazard that nonuniformly dispersed in both space and time. Over a decade, several watershed areas are frequently suffering from flood disaster, which causes massive destruction and loss of lives, farmlands, crops, access roads, and houses [8]. The effective way of flood control and reducing its negative impacts is by the construction of dams, water conveyance structures, culverts, canals, and reservoirs [9]. Many control structures are not solely constructed mainly for dealing with flood control only. However, sometimes, hydraulic structures are purposely built for flood control only. In the designing and building of flood control structures, some vital point of views must be taken into consideration in such that the cost of construction of such a project structure should be of benefit, concerning the damage reduction and the public interest when comparing to similar benefits to be derived by the alternative means. Also, the flood control structures should be reliable and effective as predicted. Even in some instance, the methods of controlling floods should rather be automatic, not manual.

2.2 Power generation

Hydropower generation is the production of electrical energy from running water through turbines without reducing its quantity. The flexibility; long-lasting, storing capability; less environmental pollution; and the cost-effectiveness of hydropower plants make it attract more investment as a renewable energy source and role as a way of drought mitigation [10]. It has been demonstrated that hydropower generated about 16.4% of the global total electricity supply equivalent to the installed capacity of about 1064 GW [9]. The hydropower system is the leading global source of an estimated 71% of total renewable energy. Furthermore, hydropower plant reservoirs can also be used as a tool in minimizing the adverse impacts of climate change and in achieving sustainable development goals [11].

2.3 Navigation

Inland water transportation plays a significant role in the national and global markets. Building dams and draining of river streams will considerably raise the capacity of inland water transportation, thereby allowing the smooth movement of a shipping vessel. An important point to note is that a chain of storage reservoirs would advance navigation depth, straightening out navigation channels, and support the passage of both small, medium, and even large ships. However, it is recommended to provide pathways or locks for vessels when dam structures are built on a large river stream for easy navigation from upstream to the downstream. Also, the topography of the surrounding environment should be taken into consideration. Hence, the pathways might be an integral part of the dam or a completely different structure.

2.4 Irrigation schemes

Recently, it was reported that about 20% of the global total arable land is under different forms of irrigation schemes. More than 70% of freshwater withdrawn from rivers is utilized for irrigating crops, and 75% of the total water hardly returns to the rivers [1]. In many regions of the world, with water scarcity, farming without irrigation would not be possible. The quantity of water kept in the storage reservoirs and the power required for water pumping are provided by hydropower plants, which are integral parts of the multipurpose hydraulic structure. In the present world, irrigation projects depend on the supply from multipurpose hydraulic dams, reservoirs, and rivers. For irrigation schemes to be successful, the water supply from sources must be adequately available whenever needed and at a reasonable cost of investment. Also, the operation and maintenance of such a structure should be smooth and cost-effective.

2.5 Municipal and industrial water supply

A large quantity of freshwater is being consumed daily by food processing; mineral mining and processing; textile, paper, and pulps; nuclear and thermal power plants; and drugs and pharmaceutical, petrochemical, and metallurgical industries, among others. However, some of the major industries that use a large volume of water are nuclear and thermal power plants. To meet both domestic and industrial needs, due to the higher demand for water by many industries, especially in industrially developed nations, large capacity storage structures are always built to store local rainfall runoff and water diverted from other river basins. Multipurpose hydraulic structures are the primary storage and sources of most water supply for domestic and industrial purposes. Although public water consumption constitutes nearly only 10% of the water consumed by the industries, still the immediate needs of public water supply must be taken seriously [12]. The water supply from hydraulic projects should always meet the standards of quality required for domestic and industrial uses in terms of its color, test, hardness, odor, and bacterial purity. Also, the treatment methods for the water should be cost-effective and daily available all year round. Necessary control and protection measures should be provided in the river basin areas where the hydraulic project is sited which are mainly for the municipal water supply. The need for hydraulic projects is also in a region with the seasonal variation of rainfall distribution of the year.

2.6 Environment protection

Another vital reason for hydraulic projects is for environmental protection and water management, which may include farmland improvement by controlling soil erosion; environmentally friendly hydropower supply; improved quality water supply for human, animal, and industrial consumption; aquatic food supply; and recreational development [8]. Nevertheless, the negative impacts posed by the massive hydraulic structures on the environment and public safety should always be considered in the course of design and construction processes [1]. The essential environmental issues are for the well-being of people living around the hydraulic projects and to the other plants and animals for the social needs of humankind.

2.7 Recreation and other purposes

Many hydraulic projects also serve as a place for tourism, recreational, and sports activities. In fact, in some countries, sometimes hydraulic projects are

specially constructed for recreation purposes. Some recreational activities carried out at the hydraulic project sites might include swimming, fishing, boating, canoeing, scuba diving, and lakeside walking. Recreational activities provide job opportunities to the teeming population and generate incomes to the government and, at the same time, conserve the natural environment.

3. Operation and maintenance of hydraulic structures

Strategies for sustainable operation and maintenance of hydraulic structures are initiated before design and are optimized during its service life for the safety of lives and properties, which stabilizes the environment and the national economy. Consequently, improper hydraulic structures' operation and maintenance may lead to loss of life, properties, economy, and the environment. The responsibilities for the operation and maintenance of hydraulic systems vary in different countries, depending on the ownership and purposes. In Nigeria, the responsibilities rest on the central government, coordinated by the department of water resources. This section has highlighted the necessary strategies for safe operation, maintenance, and consequences due to failure. The strategies can be long term, seasonal, frequent, and daily. The primary tasks to exemplary operation and maintenance of hydraulic structures according to Chen [1] are as follows: hydrologic monitoring and forecasting, detection and mitigation of aging of structures, safety surveillance and instrumentations, and remedial actions.

3.1 Hydrologic monitoring and forecasting

Safe operation and management of hydraulic structure primarily depend on the efficiency of metrological stations to provide independent data of water regime and observation. The data obtained can be used during the analysis and prediction of future hydrologic events. Nowadays, automated facilities are installed at various locations in the catchment area to provide hydrologic data. After the analysis of the data, the forecasted value and period must be provided with some reliable accuracy. The short-term forecasting, developed on runoff and other fundamental theories, provides the basis of flood controls in the catchment. Mid- and long-term forecasting give essential information to the hydropower sector [1].

3.2 Safety surveillance and instrumentations

The continuous, systematic assessments of the physical condition of hydraulic structures without compromise are encouraged. The large capacity hydraulic structures constitute a more significant threat to downstream life and properties. Mostly, failure arises from extreme flood events and inter- or obvious structural distress, which necessitates safety surveillance and instrumentation programs to detect the possible symptom and specific problem at an early stage in hydraulic structures and create strategies for the solution to the possible abnormalities [1, 13]. The selection and installation of equipment or instrumentation at appropriate locations in the surveillance area, adequate interpretation of the surveillance data, and immediate actions are more important than the number of instruments installed.

3.2.1 Safety inspection

The safety inspection is a regular inspection of some deteriorations to determine the current state of hydraulic structures based on purposes related to the operation.

Safety inspections are categorized into routine, specialized, and periodic inspections. Specifically, the embankments of large capacity structures should be closely and routinely examined against any physical defect [13]. This inspection is categorized into routine, specialized, and periodic inspections [1], and thus, their cumulative records determine whether a defect is new, gradual, and/or rapidly changing in the structures [13]. The routine inspection aims to identify the physical deficiencies of the hydraulic structures during day-to-day operations. Periodic inspections are carried out by experienced technical crews at an interval of 2–3 years and are meant to detect physical defects on the structures by visual examination so that strategic remedial actions can be taken. Specialized inspections include earthquake and check-flood inspections. Earthquake and check-flood are identified as a potential threat to hydraulic structures. Their inspection is carried out by experienced and well-trained dam engineers. Thus, the documented reports for mitigations are then put into the remedial action plan.

3.2.2 Surveillance and instrumentation

Surveillance is the continuous monitoring of physical conditions through medium to large instruments. It is being done to check the deterioration concerning the actual performance of the hydraulic structure and its trends for compliance with the design expectations. In this operation, the collection, presentation, and evaluation of data from the equipment installed in the system are paramount. The equipment must cover critical components and should be installed at positions where normal behavior is anticipated. It is a good practice to draft an ideal instrumentational plan at an early stage to eliminate the less essential provisions until an adequate, balanced, and affordable plan is determined. In large-scale structures such as a dam, surveillance through high-level technology should be enhanced. Monitoring of change in temperature and cracks occurring in the embankments are used to reveal seepage and sediments during operations.

3.3 Remedial actions

Remedial actions are meant to prevent failures of hydraulic structures, especially the large capacity structures that pose a significant threat to lives and properties. The deficiencies are classified as minor, moderate, and major accidents [1]. Their remedial actions are necessary before the failure of the entire structure. The defects may earlier be detected through surveillance, and the defects may probably be design-related, such as improper design capacity, or construction-related such as inappropriate choice of materials. The common and challenging operation- and maintenance-related incidents are the rapid rises in seepage, overtopping of earth embankment, excessive beaching, erosion of spillway and embankments, cracking in the concrete dam and spillway, and fractured gates. The remedial actions to be considered depend on the condition of structures and hydrologic events. The remedial measures included:

1. Preventive control to reduce the condition from escalation
2. Short-term actions to modify the nearby catchment conditions, such as increasing surveillance, emergency evacuations, and lowering the overtopping
3. Long-term remedies in the structures, such as reinforcements, gates, dredging, and abdication

3.3.1 Emergency remedial actions

- a. *Erosion control*: During floods, the use of polyethylene sheeting and sandbag controls the erosion of the slope embankment [1].
- b. *Overtopping control*: Overtopping must be avoided, and the provision of temporary barrier above the predicted altitude is applied.
- c. *Seepage control*: The seepage must not be allowed to saturate the downstream slope, and if saturated, the provision of permeable material to reduce pressure buildup on the embankment is needed.

3.4 Detection and mitigation of aging

3.4.1 Aging of hydraulic structures

Aging of a hydraulic structure is referring to the time-related deformations in the properties of the material and its foundation used during construction of the hydraulic structures, which developed within at least 5 years of working period. Also, it is the entire lifespan of hydraulic structure before abdication or decommissions. The deterioration of the structures may be due to the defects developed through unusual events such as an earthquake or a result of environmental factors during service life.

3.4.2 Detection of aging

Detection of aging should start during the operation and maintenance of hydraulic structures. Factors that influence the degradation of the structural properties of hydraulic systems should be identified and must immediately be managed. Alternatively, nondestructive examinations could be essential to detect the aging of hydraulic structures. The nondestructive examinations are the direct and indirect evaluation of information regarding the state of the hydraulic structure. This is to allow for immediate interventions in the situation and avoid severe consequences. Indirect assessment of aging should be accomplished by monitoring the effects and consequences of aging.

On the other hand, the direct assessment is performed by inspecting and testing the data of the structural properties of the hydraulic structures. The laboratory experiments and the in situ assessments, where the physical and mechanical properties of the sediment, including concrete, are extracted and analyzed, are examples of destructive examination. According to Chen [1], the destructive examination with in situ tests may or may not be destructive. The destructive examinations may include (i) hydraulic pumping tests for porosity and (ii) permeability and leak detection through a physical and chemical test of catchment and leakage, among others.

Similarly, a nondestructive examination is designed to ascertain the flows of materials while it protects the object's usability, successfully nondestructive tests, and requires an understanding of its limitations and data manipulation. Various methods, such as electromagnetic, resistivity, acoustic, induce polarization, and visual assessment, are employed.

3.4.3 Mitigations for aging

Adequate mitigations of aging of hydraulic structures start during the designs, effected during construction, which continues through monitoring and surveillance

in operation and maintenance stages. The prior understanding of the factors that influence the degradation of the structural properties of the materials used in the constructions of the hydraulic structures must be scrutinized. Also, the provision of extra quality to meet the designed lifespan of the system must be put into consideration during the constructions. Alternatively, the following mitigations steps are commendable:

- a. *Analysis*: The analysis of the aging process is carried out to ascertain its severity to the safety of life, properties, national economy, and environment.
- b. *Prevention*: It is well known that all structural materials have a finite lifespan and can be affected by the environment. The prevention stage to mitigate aging of a hydraulic structure is preceded by detailed analysis to know the structure's safety and its economic condition. If the effect is infinite, immediate remedial action such as an emergency action plan is necessary. However, if the effect is finite, and the structure has an economic lifespan, then, provision of concrete structures from uniquely selected materials is encouraged.
- c. *Rehabilitations*: Many physical and chemical methods like geomembrane are employed to enhance waterproof. Additionally, the repair and replacement of corroded steels and the use of excellent impermeable materials are also administered for overlay operations.

4. Challenges facing hydraulic structures

The importance of hydraulic structures cannot be overemphasized, and therefore their maintenance and safe utilization are critical. The structures should neither leak nor erode; channels and structures should be clean and free from siltation with noncorrosive or rotten moving parts. The breakdown or failure of these hydraulic structures can lead to a disastrous situation within the surrounding areas. For instance, a catastrophic dam collapse could lead to flooding and erosion.

The challenges of maintaining hydraulic structures at the initial stage can be achieved by managing the characteristic of the flow to meet the desired goal of the project needs. According to Chen [1], this can be realized by considering the public safety and ecological, environmental, and the design objectives of each structure. Some of the challenges facing hydraulic structures and the way they can be addressed are further discussed in the subsequent section.

4.1 Erosion

Soil is a nonrenewable resource that supports human and animal life. Soil provides living beings with food, fiber, and protection from harsh environmental conditions such as high temperatures and heavy rainfall. Soil is lost due to erosion as a result of continuous cultivation of land, drastic reduction in vegetation, and collapsing of hydraulic structures such as dams. Erosion is the washing away of the topmost soil layer by the agents of erosion, including water, wind, and human activities [14]. Erosion by water is caused by overland flow and transport of sediments due to the interactive action of water flow and heavy rain droplets. In hydraulic structures, erosion can occur in canals, for example, in an unlined canal at downstream or lined canal section that receives water jet flow from a gate or pipe or water that spills over a weir. This type of erosion can be remediated by dissipating the energy of the incoming water through the construction of a stilling

basin as part of the hydraulic structure immediately downstream of the pipe or weir [15]. Another critical point of canals that is prone to erosion is the intersection of a lined and unlined canal, that is, the transition point from a lined canal to the unlined canal, as shown in **Figure 3**. This type of problem is called undermining and, if not taken care of, can cause a collapse of the lining and destruction of the structure [16]. So, periodic maintenance should be observed to solve this problem. Undermining can be avoided or controlled by the provision of cutoff that will protect the foundation of the structure.

4.2 Leakage

Leakage in hydraulic structures refers to the ability of confined or upstream water bodies to exploit the least available exit, space, or crack underneath or along the structure to escape to the downstream or unconfined surrounding area. The moment the water found these small spaces, then there is a leakage problem, which is the beginning of erosion in the area. These small openings and cracks are widened with time and intensity of leakage. Thus, the soil is washed away as time goes on and the structure will collapse. At this point, preventing the collapse of such a structure will be very difficult. Take a dam, for instance, the water level is very high at the upstream. Water can flow along the dam embankment; if no measure is taken to save the structure, it can be undermined and collapse due to erosion [17].

It has been recommended by van den Bosch and Snellen [16] to observe and identify leakages at their initial stage and correct them. Leakages in the crack can be repaired by cleaning the wall or the floor where the crack is located. Then remove any sand, clay, plant growth, or debris. Open up the crack to become broader and more in-depth. Prepare cement-sand mortar to fill the hole and smoothen it with a trowel. Provide adequate curing to the repaired crack.

On the other hand, vertical cutoffs can be constructed on the structures to obstruct the flow of water underneath and along with the structure. An example of a cutoff wall in a dam is showcased in **Figure 4a**. Similarly, drop structures can also be equipped with cutoffs to block the water flow along and underneath the structure (**Figure 4b**). The cutoffs are part of the structure, driven into the embankments of a canal by digging deep into the banks of the canal and canal bed. During the installation, the earth around the canal banks and the cutoffs must be well compacted.

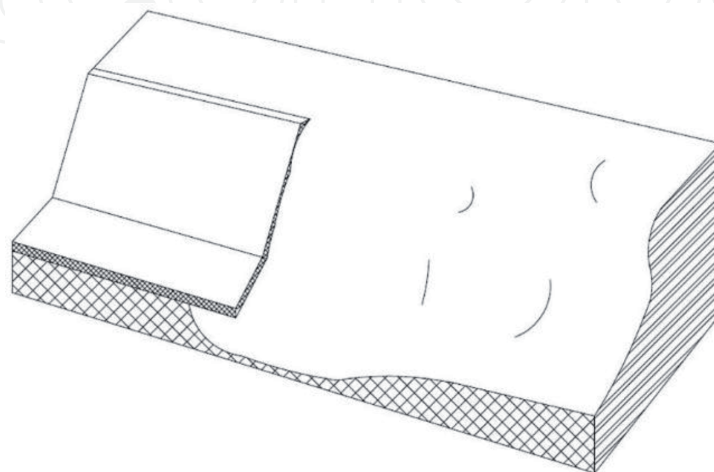


Figure 3.
Points of transition between a lined and unlined canal.

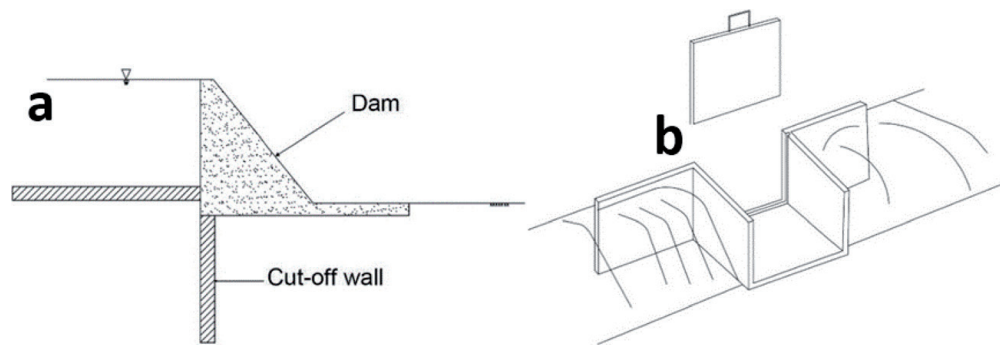


Figure 4.
(a) The function of the cutoff here was to prevent piping failure and reduce leakage or seepage. The cutoff was constructed parallel to the centerline of the dam (b) intake structure provided with a concrete cutoff wall.

4.3 Siltation

Siltation is the process of deposition of debris and sand particles and their buildup in hydraulic structures that obstruct the full functioning of the structures. The problems caused by siltation are usually the changes in water flow, changes in velocities and water levels, decreased energy dissipation, and so on. Examples of these problems include deposition of large volumes of sand in the intake chamber of pumps, which usually causes damage to the pumps and subsequent silting of the canals by sand particles. Another instance is siltation at the stilling basin. This type of sand deposits reduces the energy dissipation of the structure. Similarly, the changes in flow and velocities of water inflow division box are affected by sand particles deposited in the structure [16]. Because of these problems, large sand traps are usually constructed at the end of the upper main canal to collect the sand deposits and remove them by periodic cleaning.

4.4 Corrosion/rot

Hydraulic structures are made from different materials, including concrete, wood, or steel. These structures are liable to deterioration with time and with alternating wet and dry conditions subjected. The wooden parts in the structure, for instance, rot and decompose, whereas the steel parts corrode, as a rule, causing their expansion, and get jammed in the sliding slots. Such a condition affects the smooth operation of the structures. Routine maintenance is necessary to curtail the problems and reduce their effects. Painting of the affected parts can preserve them against corrosion. Lubrication of moving parts (steel) such as sluice gates and valves can prevent jamming.

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