

Non-Destructive Testing (DTD) for Hydraulic Structures Monitoring

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Abstract

Hydraulic structures such as weirs, bridges, drains, dams play a significant role in controlling floods, allocating water supply for domestic and agriculture activities and generating hydroelectric power. The cost of constructing hydraulic structures is high and can have terrific impacts on infrastructure and property damages well as loss of lives if it is not monitored and repaired accordingly. The threat and deterioration of hydraulic structures for instances aging, improper design, insufficient of maintenance, climate change, and natural disasters such as earthquakes or landslides also are critical issues that affect the performance of hydraulic structures and leading to deterioration and failure of these structures. Hence, it is imperative to explore the potential of Non-destructive Testing (NDT) techniques in assessing the condition of hydraulic structures, detect possible defects, and propose appropriate maintenance and repair measures to safeguard the structures. In conclusion, NDT has the potential in the management of hydraulic structures as it adds value to the monitoring of hydraulic structures, helps to improve safety, efficiency, and operational effectiveness, as well as reducing maintenance and repair costs. Furthermore, on-site monitoring and safety teams for hydraulic structures should be implemented to reduce structure failures and the use of NDT technology in repairing hydraulic structures needs to be expanded.

Key words: *hydraulic structure; non-destructive testing; NDT; threats and structural degradation; hydraulic structure monitoring and safety team*

1. INTRODUCTION

Hydraulic structures are important components in irrigation engineering systems, flood control, water supply, navigation and hydroelectric generation. Hydraulic structures such as dams, drains, and canals play an important role in preventing floods, providing water resources for domestic and agricultural use, and supporting hydroelectric power generation. The construction and development of hydraulic structures costs a lot of money and has an impact on damage to property, infrastructure and lives if not monitored and repaired due to damage.

In order to avoid damage to hydraulic structures and the safety of the structure, Non-Destructive Testing (NDT) techniques are able to help engineers and inspectors to assess the condition of hydraulic structures, identify possible defects or weaknesses,

and implement appropriate maintenance and repair measures to ensure safe and efficient operation [1].

2. TYPES AND FUNCTIONS OF HYDRAULIC STRUCTURE

There are three main categories of hydraulic structures based on their function namely:

- i. Measurement structures such as overflow channels/ weirs
- ii. Control structures such as dams and sluices
- iii. Discharge structures such as spillways

2.1. Weir

A weir is a hydraulic structure built across a watercourse such as a river or canal to control the level and flow of water. Usually weirs are designed with a flat top or a certain shape to allow water to flow in a controlled manner. Weirs are very important in water resource management and environmental protection, ensuring efficient water use and protection against natural disasters such as floods. Table 1 shows the characteristic and functions of different types of weirs.

Table 1. Characteristic and functions of different types of weirs

No.	Types of Spillway	Characteristic and Functions
1.	Sharp-Crested Weir	i. Has a sharp and thin top ii. For the measurement of water flow in a laboratory or small river
2.	Broad-Crested Weir	i. Has a wide and horizontal top ii. Suitable for larger water flows and field applications
3.	V-Notch Weir	i. Has a V-shaped opening at the top ii. Used for lower water flow measurement with high accuracy
4.	Rectangular Weir	i. Has a rectangular opening ii. Suitable for larger water flow measurements
5.	Contracted Weir	i. Having narrowed or contracted sides ii. Helps to measure water flow in a more controlled and accurate manner

2.2. Spillway

A spillway is a hydraulic structure built as part of a dam or dam to allow excess water from a reservoir or river to flow downstream in a controlled manner. Spillway is designed to handle high water flows that may occur during heavy rains or floods to prevent uncontrolled overflow of water over the dam. It is a critical component in dam design and management to ensure excess water can be channeled safely to protect the dam structure and the surrounding area, especially the downstream area. Table 2 depicts the characteristic and functions of different types of spillways.

Table 2. Characteristic and functions of different types of spillways

No.	Types of Spillway	Characteristic and Functions
1.	Chute Spillway	i. It consists of a sloping channel that drains water from the reservoir downstream ii. Used for high and fast water flow and often equipped with an energy reducer at the base to reduce erosion
2.	Morning Glory Spillway	i. Shaped like an inverted funnel on the surface of the reservoir that carries water to an underground channel ii. Used in areas with limited space or where aesthetic design is required
3.	Saddle Spillway	i. Built in the saddle or low area around the reservoir ii. Usually used as an additional spillway iii. Provides an additional path for overflow water, used when the main spillway is insufficient
4.	Shaft Spillway	i. It consists of a vertical shaft or slope that carries water from the reservoir to an underground discharge channel ii. Used in dams in hilly areas or limited space
5.	Ogee Spillway	i. Features a curved profile that follows the natural flow of water to minimize pressure and erosion. ii. Commonly used in gravity dams and concrete dams

2.3. Dam

A dam is a structure or area built in a river or stream to maintain and store water for the purpose of water supply, hydroelectricity and others. Dam is an important structure in the management of water resources that has various functions for the benefit of humans, the environment and sustainable development. Table 3 depicts the characteristic and functions of different types of dams.

Table 3. Characteristic and functions of different types of dams

No.	Types of Dam	Characteristic and Functions
1.	Storage Dam	Storing water for various uses such as drinking water supply, irrigation, and hydroelectric power
2.	Irrigation Dam	Specially designed to collect water for the purpose of irrigation of agricultural crops
3.	Temporary Dam	Built temporarily for construction purposes or to drain water temporarily
4.	Flood Control Dam	Designed to reduce the risk of flooding by retaining water during the rainy season
5.	Hydroelectric Dam	Hydroelectric power generation through stored water reservoirs

Apart from the dams listed above, there is also an infrastructure called Sabo. "Sabo" comes from the Japanese language which is a combination of "Sa" and "Bo" which

means erosion and sediment control works. The term Sabo means rock and sand reaction which is in fact an effort to prevent soil erosion in the mountainous areas, protect people and infrastructure especially downstream of the river from the threat of erosion and sediment disasters. There are two (2) types of Sabo Infrastructure, namely Open Sabo and Closed Sabo. The difference between Open Sabo and Closed Sabo Infrastructure is as in Table 4. Sabo Infrastructure is function as follows:

- i. To trap erosion/debris flow until the discharge decreased
- ii. To decrease erosion/ debris flow rate
- iii. To serve as a sediment settling zone
- iv. To guide the debris flow in preventing the spread of erosion/debris flow
- v. To control erosion/ debris flow

Table 4. The differences between Open Sabo and Closed Sabo Infrastructure

No.	Open Sabo	Closed Sabo
1.	Water flow through holes or opening/slits and large pieces of soil/ rocks/ logs will be retained	Water flow will flow through the top of the dam and trap the flow of erosion/ debris
2.	Slow down the flow of high volume water	Will quickly be filled with sediment and requires good maintenance
3.	Typically constructed at upstream and mountainous area	Usually built at downstream areas

In Malaysia, the debris flow occurred in Gunung Jerai, Yan District and Kuala Muda, Kedah on 18 August 2021 has led to a holistic structured approach using Sabo Infrastructures at Titi Hayun Recreational Forest, Yan District and Tupah Treatment Plant, Kuala Muda District [2]. It aimed to minimize the impact of debris flow, traps timber, rocks and sediment, stabilize the banks and slopes, biodiversity conservation in addition to saving property and guaranteeing public life safety.

2.4. Gate

Gates are a hydraulic structure that can be opened or closed to control the flow of water in irrigation systems, dams, canals, and water treatment plants. Gates usually made of concrete and operated manually or automatically using mechanical or electrical systems. Gates are essential component in water resource management and hydraulic systems, providing the flexibility and control needed to ensure safe and efficient operation. Table 5 depicts the characteristic and functions of different types of gates.

Table 5. Characteristic and functions of different types of gates

No.	Types of Gate	Characteristic and Functions
1.	Tilt Gate	Open or close in an upward or downward slant
2.	Lift Gate	Open or close by going up or down vertically
3.	Swing Gate	Open or close by rotating on a certain axis
4.	Roller Gate	Open or close by rolling or pulling horizontally
5.	Sluice Gate	It usually consists of a large portion of a metal plate or panel that can be moved vertically in a slot attached to the water channel structure

2.5. Bridge

A bridge is a structure built to cross a gap or obstacle such as a river, railway or road. It is built to allow the passage of pedestrians, motorists or trains over the barrier. Table 6 represents the characteristic and functions of different types of bridges.

Table 6. Characteristic and functions of different types of bridges [3]

No.	Types of Bridge	Characteristic and Functions
1.	Log Bridge	A timber bridge that uses logs that fall naturally or are intentionally felled or placed across streams.
2.	Beam Bridge	Characterized by the presence of one or more longitudinal beams that constitute the main structure, supported by substructures like piers and abutments.
3.	Truss Bridge	Characterized by an intermediate operation between an arch and a beam if equipped with inclined piers compared to the vertical.
4.	Compression arch bridge	Bridge shaped as an upward convex curved arch to sustain the vertical loads. A simple arch bridge works by transferring its weight and other loads partially into a horizontal thrust restrained by the strong abutments at either side.
5.	Suspension bridge	Distinguished by the presence of straight cables connecting a main pylon, called a mast, to the bridge deck.
6.	Cable-stayed bridge	Characterized by cables with low flexural rigidity, allowing them to assume a stable curved shape. These cables, through suspension elements, support the bridge deck. Generally made of steel.
7.	Cantilever bridge	A bridge built using structures that project horizontally into space, supported on only one end (called cantilevers).
8.	Moveable bridge	Or movable bridge, is a bridge that moves to allow passage for boats or barges

3. RESULTS AND DISCUSSION

Non-Destructive Testing or better known as Non-Destructive Testing (NDT) is a form of testing materials or components without destroying, damaging or changing the structure of the material [4]. The importance of NDT Testing in hydraulic structures is also closely related to issues such as the threat and degradation of hydraulic structures which are critical issues in the infrastructure's ability to control and manage

water effectively. Hydraulic structures such as dams, drains and canals play an important role in preventing floods, sources of supply for domestic and agricultural purposes and hydroelectric power generation. However, factors such as ageing, poor design, inadequate maintenance, climate change and natural events such as earthquakes or landslides can cause deterioration and failure of these structures. Damage to hydraulic structures can have adverse effects such as loss of life, property damage and significant economic losses. Therefore, understanding and addressing these threats and degradation is essential to ensure the long-term effectiveness and safety of hydraulic infrastructure. Threats and structural deterioration are as in Table 7.

NDT applications are widely used in the oil and gas, manufacturing, shipping, aerospace, railway and power plant industrial sectors and potentially in the management of hydraulic structures. Table 8 shows the types of NDT that can be used in the safety monitoring of hydraulic structures. NDT allows early detection of damage to hydraulic structures before they develop into more serious problems. This allows remedial action to be taken quickly to prevent further damage. NDT testing is also useful in determining maintenance and upkeep requirements. Through information from NDT testing, managers can optimize maintenance schedules, handling and operation of hydraulic structures and reduce costs associated with unnecessary maintenance. By detecting damage early and proactively performing necessary maintenance, NDT can help reduce the cost of repairing and replacing affected hydraulic structures.

Table 7. Treats and Structural Deterioration

No.	Treats	Characteristic
1.	<i>Overtopping</i>	i. The capacity of the channel is insufficient causing overflow/ overtopping occurs ii. Insufficient free board to accommodate storms and flood events will result in overflow at the top of the dam body and the bank walls around the reservoir iii. Dams at risk of overtopping hazard are Batu Dam, Timah Tasoh, Bekok and Sembrong [5] iv. The height of the crest level is likely to be lowered in the event of other failures such as seismic movement and internal erosion
2.	Seepage Failure	i. Seepage failure - due to water moving slowly through the dam and/or percolating slowly over a long period of time through the base of the hydraulic structure ii. Will result in embankment, or foundation, or damage to the concrete structure iii. If not properly controlled, seepage can gradually erode the soil from the embankment or at its base, resulting in dam failure iv. A steady or sudden drop in normal lake levels is another indication that seepage is occurring v. Higher water levels can lead to extreme danger and risk when hydraulic structures such as dams occur, especially to residents in downstream areas
3.	Aging/ Failure of Hydraulic Infrastructure	i. As of 2023, a total of 16 out of 55 Dams in Peninsular Malaysia (Water Supply) have exceeded 50 years [6] ii. Floods and other extreme environmental events are becoming more frequent and severe, which can exceed the design limits of dams and accelerate their aging process and risk structural failure

	iii.	Water supply disruption - Reduction of reservoir capacity (Sedimentation problem)
	iv.	Risk to the people in the downstream part of the river
4. Scouring and Erosion	i.	Erosion of channel bottoms and edges due to rapid water flow or bottom erosion downstream of hydraulic structures or turbulent flow and eddy currents (<i>arus pusar</i>) is called scour
	ii.	Scouring at the Foot of the Dam The formation of large holes in the river bed near the dam due to the rapid flow of water, which can affect the stability of the dam structure
	iii.	Bridge Scouring Strong water flow around bridge piers or abutments can cause localized erosion that weakens bridge supports
	iv.	Spillway Scouring Heavy water flow through the spillway can cause erosion that damages the spillway structure and potentially causes failure
5. Earthquake	i.	Earthquakes are the main threat and influence the dams, especially old dams
	ii.	An earthquake is expected to cause the dam failure
	iii.	For example: The Timah Tasoh Dam crack in Perlis, Malaysia occurred due to earthquake in Timah Tasoh [7]
	iv.	In Peninsular Malaysia there have also been several earthquakes with the local epicenter at Bukit Tinggi in Pahang, Kenyir Dam in Terengganu, Kuala Pilah in Negeri Sembilan as well as Manjung and Temenggor in Perak with a strength range between 1.6 to 4.6 on the Richter scale that occurred in 1984, 1985, 1987, 2007, 2009, 2010 and 2013 [8]
6. Climate Change	i.	Climate change is a global threat that will affect the function and safety of hydraulic structures in Malaysia
	ii.	Malaysia receives high rainfall which always leads to flooding and causes the failure of water control structures such as dams, barrages and flood control bulls
	iii.	Rising sea levels and stronger coastal storms create challenges for states with coastlines and communities living near the sea.

Table 8. Types of NDT that can be used in the safety monitoring of hydraulic structures

No.	Types of NDT		Functions
1.	Ultrasonic (UT)/ Sonic Transmission	Testing Pulse	Using ultrasonic waves to detect defects such as cracks, wall thickness, or the presence of foreign materials in hydraulic structures
2.	Gamma Testing	Radiography	Using gamma rays to obtain images of materials that cannot be seen with the naked eye, such as the presence of cracks or corrosion in water lines
3.	Visual Testing (VT)		Direct Testing using the naked eye or visual equipment to detect signs of damage such as cracks, erosion or loss of material on the hydraulic structure
4.	Eddy Current Testing		This technique involves the use of electromagnetic fields to detect changes in electrical concentration in materials that may be caused by the presence of defects such as cracks or erosion
5.	Penetrant Inspection		A process where a special liquid is used to fill cracks or defects on the surface of a structure, then this liquid is removed and a dye is applied to show the defect
6.	Radiographic (RT)	Testing	Using X-rays or gamma rays to produce images of the internal structure of materials, allows detection of cracks, defects, or material thicknesses that cannot be seen directly
7.	Magnetic Testing	Particle	Using ferromagnetic particles placed on the surface of the structure. When a magnetic field is applied, the particles will gather around the crack or defect, indicating the location of the damage

Some application of NDT was applied worldwide such as in India, Sonic Pulse Transmission Technique is used to figure out weak zones comprising of voids, cracks, etc. in concrete and masonry structures like dams, Aqueduct, Canals and others thus, it is able to check the homogeneity of the material forming the structure. Since, ultrasonic pulse transmission technique has got limitation of penetration depth up to 5 meter, sonic pulse transmission technique is adopted for depth exceeding 5 meter [9]. Figure 1 shows NDT by sonic transmission in India while Figure 2 depicts NDT by Visual Inspections using Drone at United States of America.



Figure 1. NDT by Sonic Transmission [9]

Left: NDT by sonic transmission technique at Vakkileru Aqueduct, India. Right: NDT by sonic transmission technique at Sardar Sarovar Dam, Gujarat, India.



Figure 2. NDT by Visual Inspections using Drone at United States of America [10]

4. CONCLUSION/ WAY FORWARD

Non-destructive Testing (NDT) has potential in the management of hydraulic structures where NDT provides added value for hydraulic structures monitoring, improve safety, efficiency and operational effectiveness, while reducing maintenance and repair costs. On-site Hydraulic Structure Safety/ Monitoring Teams are beneficial to reduce structural failures and the use of NDT technology in managing the performance of hydraulic structure needs to be expanded. Until now, only the dam structures are monitored by the Malaysian National Committee for Large Dams (MYCOLD).

In addition, all relevant agencies play important roles in ensuring that hydraulic structures in Malaysia are regularly inspected and maintained using NDT methods to ensure the safety, reliability and sustainability of the country's water resources. Innovation development for Green Hydraulic Structures focuses on integrating environmental sustainability with current water management systems are important to explored further too.

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