



 Research Article

Underground Hydraulic Structures Technical Condition Monitoring Systems

Submission Date: January 12, 2026, **Accepted Date:** February 10, 2026,

Published Date: February 28, 2026

Crossref doi: <https://doi.org/10.37547/ijasr-06-02-02>

Journal Website:
<http://sciencebring.com/index.php/ijasr>

Copyright: Original content from this work may be used under the terms of the creative commons attributes 4.0 licence.

Professor Ganiyev In'omjon Gulomovich

1st-year Master's student, Specialty 70730602 "Geotechnics and Underground Hydraulic Structures", Jizzakh Polytechnic Institute, Uzbekistan

Eshpo'latova Malika Ulug'bek qizi

1st-year Master's student, Specialty 70730602 "Geotechnics and Underground Hydraulic Structures", Jizzakh Polytechnic Institute, Uzbekistan

ABSTRACT

Underground hydraulic structures (hydraulic tunnels, drainage collectors, galleries within hydraulic units, water conveyance chambers, underground water reservoirs, etc.) are long-service-life engineering facilities belonging to a high-risk category. Over time, the technical condition of these structures may deteriorate due to hydrostatic pressure, seepage flows, aggressive environmental conditions, soil deformation, seismic effects, and operational loads. This paper presents the scientific foundations of monitoring systems used to assess the technical condition of underground hydraulic structures and to ensure safe operation, including sensor and measurement technologies, digital data architecture, diagnostic indicators, and risk-based decision-making models. In addition, the advantages of integrating traditional geodetic observations with modern IoT/SCADA solutions, fiber-optic monitoring technologies (DAS/DTS/FBG), non-destructive testing (NDT) methods, the "digital twin" concept, and predictive maintenance approaches are analyzed. As a result, a comprehensive monitoring model is proposed, and practical recommendations are provided for continuous control of structural serviceability, seepage stability, and overall structural integrity.

KEYWORDS

Underground hydraulic structures, monitoring, seepage, piezometer, inclinometer, deformation, fiber-optic sensors, SCADA, IoT, NDT, digital twin, risk.

INTRODUCTION

Underground hydraulic structures play a strategic role in water management and energy systems by enabling water conveyance, pressure regulation, drainage, and safety functions. Such structures typically operate in complex geological conditions with high humidity and chemically aggressive environments. Due to soil–structure interaction (SSI), defects may develop over time, including cracking, widening of seepage paths, reinforcement corrosion, concrete carbonation, delamination of lining layers, and settlement [1].

The main objective of monitoring is to detect hazardous changes in technical condition at an early stage, reduce the probability of failure/accidents, and optimize operation and maintenance costs. Modern monitoring approaches are increasingly shifting from “periodic inspections” to “continuous digital surveillance”.

Research Aim and Objectives

Aim: To develop a scientific and practical model for monitoring systems that enables near-real-time assessment of the technical condition of underground hydraulic structures, identification of risk indicators, and implementation of predictive management [2].

Objectives:

- ✓ to substantiate monitoring targets and key control parameters (KPIs);

- ✓ to develop criteria for selecting measuring instruments and sensor technologies;

- ✓ to define the data architecture for collection–transmission–storage–analysis;

- ✓ to apply diagnostic models for relevant damage mechanisms;

- ✓ to propose a risk-based decision-making algorithm.

Conceptual Model of a Monitoring System

A monitoring system for underground hydraulic structures typically consists of five layers:

1. Sensors and measuring devices (deformation, pressure, seepage, vibration, etc.)

2. Data acquisition module (datalogger, RTU/PLC)

3. Communication channels (fiber-optic communication, GSM/LTE, radio, Ethernet) [3]

4. SCADA/IoT platform (visualization, alarms, data archiving)

5. Analytics and decision-making (diagnostics, forecasting, risk assessment, recommendations)

This workflow can be expressed as:
Measurement → Verification → Filtering →
Diagnostics → Forecasting → Decision →
Planning.

Key Parameters to Be Monitored

Monitoring parameters are classified into three groups.

1. Hydraulic and Seepage Parameters

- ✓ piezometric pressure p
- ✓ seepage discharge q
- ✓ water level (groundwater table)
- ✓ drainage system efficiency
- ✓ turbidity indicators and chemical aggressiveness (pH, sulfates)

Instruments: vibrating wire piezometers (VWP), flow meters, pressure sensors, water quality sensors.

2. Geometric and Deformation Parameters

- ✓ settlement sand uplift
- ✓ convergence (closure of the tunnel cross-section)
- ✓ lateral displacement (horizontal deformation)
- ✓ crack width and crack propagation
- ✓ stress/strain in the lining

Instruments: inclinometer, extensometer, convergence meter, crack gauges, strain gauges, total station.

3. Dynamic and Vibration Parameters

- vibration velocity v , acceleration a
- resonance frequencies, mode shapes
- seismic excitation signals

Instruments: accelerometer, geophone, seismic station, DAS (distributed acoustic sensing).

Sensors and Technologies: From Conventional to Digital

1. IoT/SCADA Integration

SCADA systems provide real-time monitoring, alarm management, trends, event logging, and automated reporting. IoT enables more cost-effective and scalable sensor networks and facilitates integration with cloud-based analytics services.

2. Fiber-Optic Monitoring (DAS/DTS/FBG)

- ✓ DTS - distributed temperature sensing (identification of seepage paths and wet zones)
- ✓ DAS - distributed acoustic sensing (crack initiation, flow noise, micro-damage detection)
- ✓ FBG - fiber Bragg grating sensors for high-precision strain and stress measurements

Fiber-optic systems offer long-distance, multi-point measurement and strong immunity to electromagnetic interference.

3. Non-Destructive Testing (NDT) Methods

✓ ultrasonic pulse velocity (UPV),
ground penetrating radar (GPR)

✓ rebound hammer, thermography

✓ reinforcement cover and
corrosion tests

NDT methods are essential for detecting hidden
defects in the lining/pavement layers.

Data Analysis: Diagnostics, Forecasting, and “Digital Twin”

1. Diagnostic Indicators [4]

✓ rate of trend change: $\Delta x / \Delta t$

✓ threshold values and warning
zones

✓ multi-parameter indices:
 HI (Health Index)

For example, a general “condition index” can be
defined as:

$$HI = \sum_{i=1}^n w_i \cdot \frac{x_i}{x_{i,lim}}$$

where x_i is the measured parameter, $x_{i,lim}$ is the
limit value, and w_i is a weighting coefficient.

2. Predictive Maintenance

Using time-series models, regression, Kalman
filtering, or machine-learning methods (e.g.,
anomaly detection), processes that may lead to
failure can be evaluated in advance.

3. Digital Twin

A digital twin is the integration of a real
structure’s BIM/FEA model with real-time sensor
data. This approach:

✓ clarifies load–response
relationships,

✓ enables “what-if” scenario
analysis,

✓ supports justification of
strengthening and repair alternatives.

Risk-Based Decision-Making Model

Monitoring outcomes can be expressed in terms
of risk:

$$Risk = P_f \times C$$

where P_f is the probability of failure
(accident/unsatisfactory performance) and
 C represents consequences (economic loss, safety
impact, environmental damage).

A prioritization (decision) index can be defined
as:

$$PI = \alpha \cdot P_f + \beta \cdot \frac{C}{C_{max}} + \gamma \cdot \frac{1 - R}{(1 - R)_{max}}$$

where R is resilience, and α, β, γ are weighting
factors.

DISCUSSION: Practical Recommendations for Implementation

- ✓ The monitoring design should match the structure's risk class and service life [5].
- ✓ Sensor placement should be optimized for zones with high seepage probability, joints, and stress concentration areas.
- ✓ Data quality control (calibration, validation, noise filtering) must be mandatory.
- ✓ Threshold values should combine regulatory requirements with empirical/field data.
- ✓ Emergency response planning should be linked directly to monitoring alarms and warning logic.

CONCLUSION

Safe operation of underground hydraulic structures directly depends on the scientific validity and comprehensiveness of monitoring systems. This paper presented monitoring architecture covering hydraulic-seepage, deformation, and dynamic parameters; IoT/SCADA integration; fiber-optic technologies; NDT methods; and digital twin-based diagnostic and predictive management approaches [6]. The proposed risk-based decision model connects monitoring results with practical strengthening and maintenance planning. Consequently, the

probability of accidents decreases, service life increases, and operation costs are optimized.

REFERENCES

1. ICOLD. Dam Safety Guidelines and Monitoring Recommendations.
2. USACE. Instrumentation of Dams and Levees. Engineering Manuals.
3. ISO 18674 (Parts 1–4). Geotechnical Monitoring and Instrumentation.
4. FHWA. Geotechnical Instrumentation and Monitoring for Transportation Projects.
5. ACI / fib. Guidelines on concrete durability, cracking, and structural health monitoring.
6. Pellicer, E. et al. Structural Health Monitoring and Digital Twin Approaches in Civil Infrastructure (review papers).