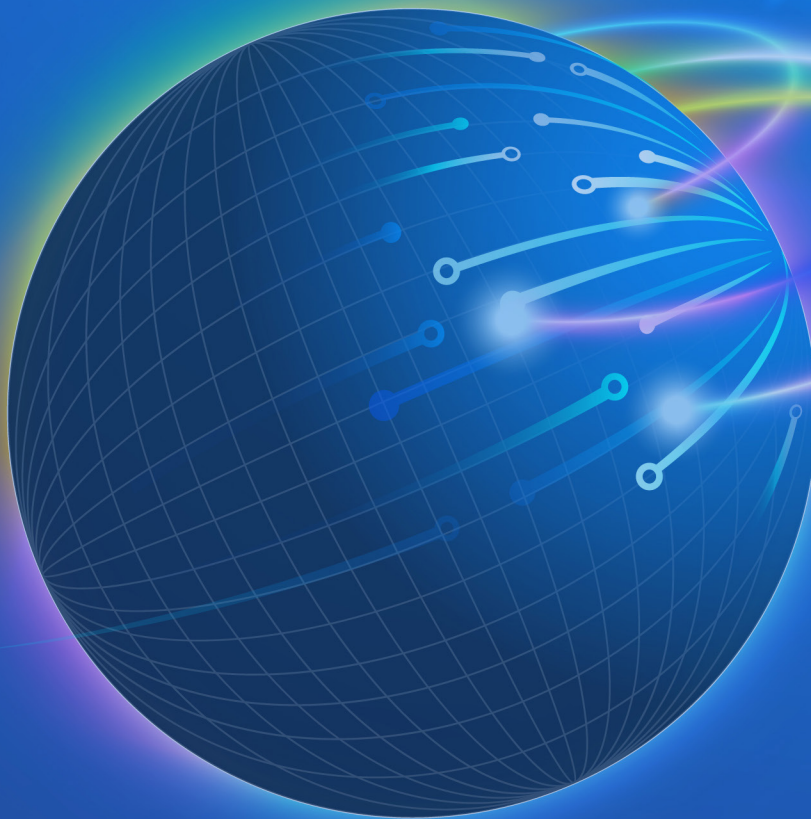




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An Experimental Approaches of Structural and Hydraulic Performance for the Kaptai Dam, Bangladesh

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ABSTRACT

Bangladesh has a major hydro power plant, Kaptai Dam (which provides 10% of national power) and is more than sixty years old, which means it is at risk of performance due to the obsolescence and sedimentation. There was prior research only on the displacement and power generation but left out the reservoir capacity loss rate, structures of a dam under loads, and water management efficiency during climate change, which is not supportive of reconstruction. The research seeks to fill the gaps through elaborate civil engineering tests: historical evaluation of design/engineering of the dam, objective measurements of its structural/hydraulic performance and sustainability in water management. Some of the methods are ASTM-compliant NDT, concrete core tests, ANSYS FEM, bathymetric surveys, sediment sampling and power data regression deployed here. Findings indicate a 19% decrease in concrete compressive strength, focused tensile stress, a 26.2 MCM/year sedimentation (a drop in storage of 25.1 per cent and a drop in power efficiency of 18 per cent) and a vicious circle of sedimentation and structural degradation. It points out flaws of reactive maintenance, suggests the combined management approach, and offers a unified framework (monitoring, sediment / watershed management) to operate safely and efficiently in the future dam construction.

INTRODUCTION

Background and Contexts

Bangladesh faces the dual challenges of rising energy needs and growing water stress. Thus, the sustainable management of the country for a large-scale hydraulic construction has been more crucial. Therefore, to meet-up uprising energy demand and also utilizing water resources, the Kaptai Dam that stands as the sole major hydroelectric infrastructure throughout the country, represents an immense feat of civil engineering (Nobi, 2021; Mojid, 2020). This construction shaped the ecology, economy, and livelihood of the southeastern part. Usually the dam situated on the Karnaphuli River of Bangladesh which has been supplying around 10 percent power in the national greed (Ahmed *et al.*, 2025). The dam has also been regulating flood hazard at downstream, and supporting water supply for irrigation in agro-sector areas. The Kaptai dam's operation which exposed it to cumulative pressures: upstream sediment erosion, fluctuating water levels in the reservoir, and extreme rainfall—all of which challenge the dam's structural integrity and hydraulic performance (Rayhan *et al.*, 2021). According to the report (Suman *et al.*, 2021) such infrastructure decades old, forms part of national power production and it is a significant controller of the Karnaphuli River basin. Nevertheless, the dam and the dam reservoir, the Kaptai Lake, after more than sixty years of operation are under increasing sedimentation and infrastructure age pressures and changing hydrology threatening the sustainability of this important national resource. The stable operation of the dam is becoming increasingly important for energy security and disaster

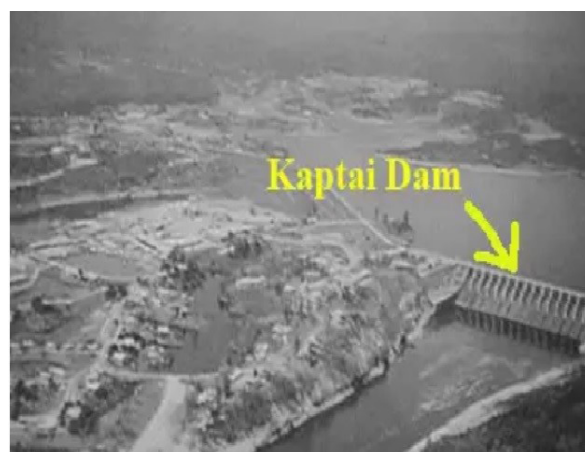


Figure 1: Kaptai Hydropower Plant Project at Rangamat District of Bangladesh

vulnerability, and its state has become a national priority. Initial research and field observations (Puppala, 2021) revealed two fundamental difficulties in water resource management. Firstly, structural deterioration, such as cracks in the concrete spillway and reduced dam stability due to waterlogging. Secondly hydraulic inefficiency, i.e., reduced water drainage capacity due to silt entrapment in the hydraulic channels and uneven distribution of flow through the spillway gates (Iqbal & Riaz, 2024; Bashar *et al.*, 2025; Amin & ElZahar, 2023). Although the historical context of Kaptai Dam, including its overall socio-economic impact, has been documented in the literature, a significant gap has been observed in terms of a thorough civil engineering analysis, through

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which the developmental history of Kaptai Dam can be systematically related to its current operation and management issues (Rana *et al.*, 2025). Previous studies have tended to look at individual aspects such as displacement problems or overall power generation, and have not conducted a holistic technical examination of the underlying infrastructure issues. Some of the important issues that have not been effectively addressed are the rate of reservoir capacity loss due to silt accumulation, the strength of the dam structure under different load levels, and the effectiveness of the water management system under climate change (Miah *et al.*, 2021). This does not ensure that engineers and policymakers can come up with evidence-based measures for the future reconstruction of dams.

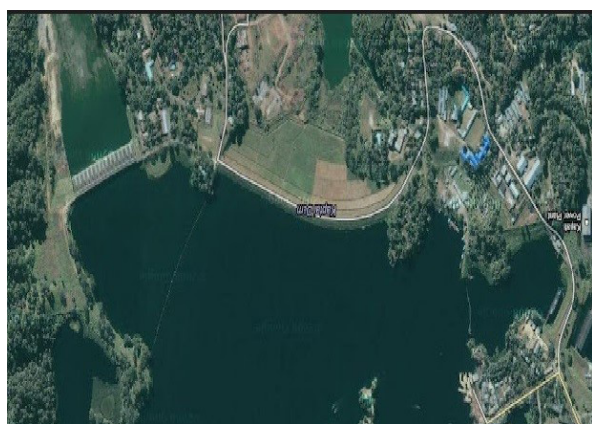


Figure 2: Kaptai Dam with Spillway and Power Plant

Research Aims and Significance

The current paper intends to address the existing deficit by a detailed civil engineering examination. Its fundamental goal is a historical analysis of the design principles and engineering methodologies involved in the development of the hydro dam. Secondly reveal a quantitative assessment of the present structural and hydraulic results of Kaptai Dam. Particular focus on sediment deposition and its influence reservoir capacity and turbine efficiency. Moreover, the current work aims to evaluate existing water resource management strategies in terms of sustainability.

This study has two types of contributions. Overall, academically, it will present a groundbreaking case study of the long-term performance of large hydropower projects in geo-sensitive and hydrologically sensitive geographical areas that will be beneficial for hydraulic engineering and sustainable management of infrastructure. Practically, the results will be applicable to the Bangladesh Power Development Board and water resources management agencies to generate useful knowledge for conducting critical maintenance plans, sediment management practices, and potential reconstruction plans. This study will ultimately attempt to create a robust framework to keep Kaptai Dam as a stable energy source and water security pillar of Bangladesh in the future.

LITERATURE REVIEW

Integrated Assessment of Dam Performance

Researchers (Erpicum *et al.*, 2020; Wakjira, 2022) underscored that the hydraulic and structural behavior of large-scale dams is a very important research topic in civil engineering, which directly affects their safety, efficiency and lifespan. Research in this field is interdisciplinary and includes materials degradation, sediment transport and hydropower modeling. This literature review is a synthesis of the literature related to the experimental evaluation of Kaptai Dam.

The sustainable performance of a large dam such as the Kaptai Dam requires a deep understanding of its long-term structural and hydraulic behavior (Salehin, 2024). While the available studies provide an informative idea, the literature review identified a gap that cannot be ignored: there is a lack of collective, experimental research on how structural integrity is linked to hydraulic performance for a thorough assessment of a dam. In this section, previous work is reviewed, gaps in the subject knowledge are defined, and the current research is presented as a necessary improvement.

Thematic Synthesis for Structural Assessment Longs

In order to dam research on old concrete gravity dams has always pointed to material degradation as a major problem. In the world, non-destructive testing (NDT), namely ultrasonic pulse velocity (UPV) and rebound hammer testing, have proven to be the basis for in-situ testing of concrete properties (Chouinard *et al.* 2018; Malm 2016). These techniques have been praised as practical and are known to need to be calibrated with destructive core testing to accurately determine their strength. Furthermore, the Finite Element Method (FEM) has become an important analysis tool, as demonstrated by Wang *et al.* (2024), where it is possible to simulate situations under the influence of complex loads and define problematic stress areas that cannot be observed in simplified forms of analysis.

However, there is a major disparity in the use of this set of methods in the context of the Kaptai Dam. Although the authors of studies such as Rana *et al.* (2025) have reported structural aging results on an anecdotal basis, there is a notable lack of available, data-driven studies using a combined NDT-FEM method to measure the current mechanical condition of its concrete. This research work directly fills this gap in that it is organized by systematically applying these global best practices to provide an empirical basis for the structural health of the dam.

The Hydraulic Challenge: Sedimentation as Foremost Controlling Factor

The literature clearly states that reservoir sedimentation is the biggest threat to the overall hydraulic efficiency and economic viability of dams, especially in sediment-rich river systems like those in South Asia. Byson (2019) points out that the world is losing reservoir capacity at an

alarming rate, which is acutely experienced in this region. The remote sensing analysis by Chakma *et al.* (2021) is one of the studies specific to Kaptai Dam and is able to illustrate the macroscopic problem of storage capacity loss. However, their work is a very important initial step, but not the final one. It also cannot provide ground-truth, bathymetric measurements to determine the exact rate of sedimentation, and it does not explore the composition of the sediment itself, which is essential for understanding its frictional force on turbines (Zhang & Se, 2021). This is the second major gap: a shift between the occurrence of sedimentation and its mechanisms and direct engineering effects. The phenomenon of capacity loss has been documented in previous studies, but not its magnitude with extreme precision, nor how sediment properties are simultaneously degrading mechanical components and changing hydraulic flow patterns.

The Disconnect: Individual Analyses and the Requirement to Integrate

A critical review of the literature on Kaptai Dam reveals a disjointed pattern of disciplinary approaches. Studies are generally divided into socio-economic impacts (e.g., displacement), historical accounts, or general environmental reviews. The few technical studies that exist, such as Rahman *et al.* (2019), are generally limited to single parameters (e.g., power generation) or general sediment flow, but do not reveal the underlying structural-hydraulic interactions.

The main research gap that my study will address is: a deep structural deficit. A dam has structural and hydraulic systems, which are not independent. For example, the presence of sediment (hydraulic problem) intensifies the force of lateral forces on the dam system, while possible cracks or holes (structural problem) can change the path of water and increase internal erosion. This synergistic relationship has been well proven theoretically in dam engineering worldwide (e.g., Guimarães & Da Silva Lima, 2021) but has not yet been empirically investigated in the case of the Kaptai Dam. The existing fragmented knowledge cannot be used to develop a holistic management strategy because it does not capture such important feedback loops.

Model for Assessing an Integrated Performance

To overcome these shortcomings, this paper presents a conceptual model (Figure 1), which places the overall performance (OP) of Kaptai Dam as a variable in two interdependent pillars, namely structural assessment (SA) and hydraulic assessment (HA). This model goes beyond descriptive analysis where empirical, measurable variables are described in each pillar:

This framework explicitly includes the external context of aging and the history of management. Its main contribution is the integration step, where the interactions between SA and HA are thoroughly studied. This model provides analytical clarity that is lacking in previous

literature: on the one hand, presenting a structured approach to diagnose existing problems, on the other hand, to understand the causal interrelationships of these problems, which will allow predicting the maintenance process and sustainable management of the Kaptai Dam and other infrastructures.

MATERIALS AND METHODS

This paper presents a combination of experimental methods for measuring the structural and hydraulic performance of Kaptai Dam. These two strands of the methodology are complementary and are divided into two strands (Figures 3 & 4) as shown in the conceptual study framework in the workflow.

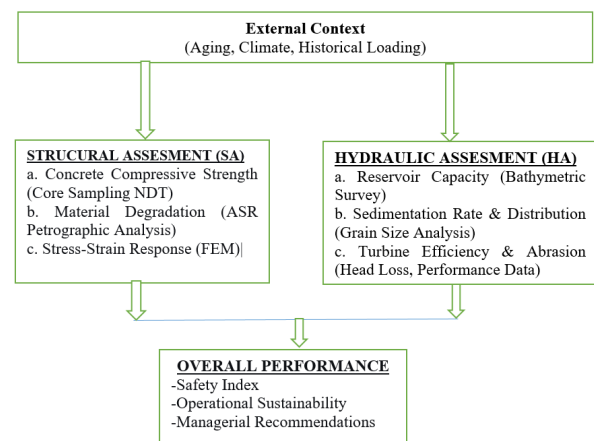


Figure 3: Study Model for Assessing the Engineering Performance of Kaptai Dam (Source: Adopted by the Content Analysis)

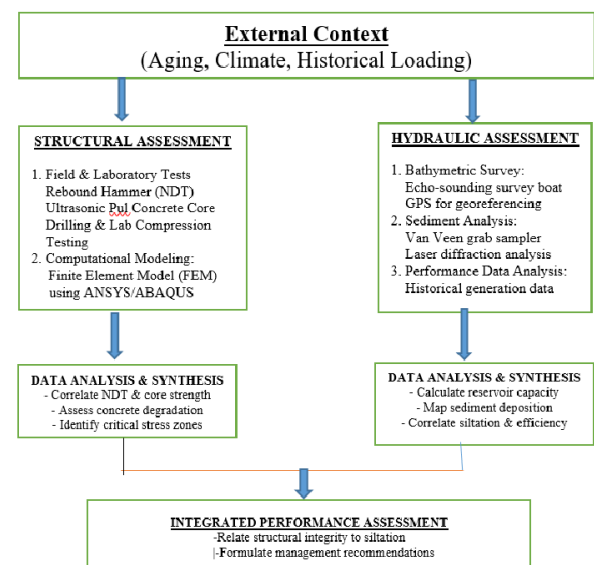


Figure 4: Schematic Workflow for Experimental Approach Study Model for Assessing the Engineering Performance of Kaptai Dam

Structural Performance Assessment

Rationality for Parameter Choosing and In-Situ Non-Destructive (NDT)

The parameters used in NDT were based on ASTM C597 and ASTM C85 to make sure that in-situ concrete status of the dam was thoroughly considered. Spatial variation was captured by using systematic grid survey (1.5m x 1.5m) of the accessible surface of the non-overflow and the spillway sections.

- **Instrumentation:** To measure surface hardness a Proceq Schmidt Rebound Hammer (Model N) was used and a PUNDIT PL-200 Ultrasonic Pulse Velocity Tester to measure the transit time of ultrasonic waves. **Data validation and Reliability:** The measurement of NDT at each grid point were performed three times to reduce the error of an operator by recording the average value of NDT at that point. Rebound Number (RN) and Ultrasonic Pulse Velocity (UPV) were also cross-verified to be able to detect anomalies. All equipment was calibrated pre to the field campaign and after using standard reference blocks.

Concrete Core Sampling with Lab testing

The data of the NDT needed to be gained through calibration using the vales of direct mechanical properties, and as a result, concrete cores were extracted.

- **Justification of Parameter Selection:** The selection of parameters was justified as the number of cores (n=10) and their positions has based on the results of NDT to highlight on the ground of usual and unusual scores to have a representative sample of the state of the dam. core dimensions (100mm diameter, L/D=2.0) were in align with ASTM C42/C42M.

- **Reproducibility and Accuracy:** Cores were sampled in a uniaxial compressive testing machine with 2,000 kN compression testing machine in complete adherence to ASTM C39. To determine the modules of elasticity, the stress-strain behavior was measured. In order to evaluate the degradation processes, petrographic analysis was performed on thin sections per the ASTM C856 standard to evaluate Alkali-Silica Reaction (ASR) as well as other types of deterioration. Such lab verification presents an ultimate standard of the NDT data.

Finite Element Modeling (FEM)

Model Set-up and Justification of Input: ANSYS software has been used to develop a 3D finite element model. The geometry of the model made on the initial design of the dam. Naciri *et al.* (2025) stressed that the material properties (desnity, Poisson ratio, comprehensive strength and modulus elasticity obtained through core test) were attributed to reflect the prevailing condition of concrete.

- **Analytical Reliability Check:** The load cases of hydrostatic pressure at Full Reservoir Level (FRL) and seismic loads accordance with the Bangladesh National Building Code (BNBC). to make sure that results were also independent of element size, a mesh sensitivity analysis was carried out. The model verified by the comparison of

calculated displacements with the historical monitoring data, where available, such that the FEM reliability serves the way of the dam to react in response to its structure.

Assessment of Hydraulic Results

Bathymetric Study and Capacity Loss Calculation

- **Reproducibility Method:** The bathymetric survey method was performed using a Norbit iWBMS multibeam echosounder with a differential GPS (DGPS) positioning accuracy of centimeter level. It was decided to use 100% overlapping survey lines to cover the entire area and avoid data gaps.

- **Data and Validation Processing:** The current study included QPS Qimera applications for sound velocity profile correction, tidal adjustment. Data obtained from the Digital Elevation Model (DEM) was compared with the initial topographical map at the time of commissioning of the dam. The prismoidal formula was used to verify the storage capacity calculation and the error margin was estimated to be less than 2, which is very accurate in assessing sedimentation.

Sediment Selection and Examination

- **Systematic Sampling Technique:** At least 15 locations where sediment samples were collected. These were previously determined, using a Van Veen grab sampler. The sampling method was stratified by random sampling as the upper, middle and lower parts of the reservoir and the area around the main flowing river and dam were to be covered.

- **Analytical Reliability:** The grain size determination analyzed with a Malvern Mastersizer 3000 laser diffraction analyzer. Standard reference materials were used to calibrate the instrument in each analysis batch. Triplicate analyses (per sample) were performed to determine the reproducibility of the particle size distribution curve, which is essential for determining the friction potential of the turbine.

Check Hydropower Efficiency

- **Data Collection and Validation:** Bangladesh Power Development Board accessed historical data on power generation and water source and discharge during the period 2000-2024. The data was brought under quality control process where discrepancies or absence of data were identified and corrected by cross referencing the data with the operating logbook.

- **Performance Degradation Model:** Calculation of performance was performed using the basic power equation as $P = \rho * g * Q * H * \eta$. The efficiency values obtained over time were plotted against the original efficiency curve of the turbine. To measure the rate of performance degradation, a statistical regression analysis was conducted to provide a valid measure of the decreasing hydraulic efficiency of the dam.

RESULTS AND DISCUSSION

Here, the integrated experimental campaign analyses of

Kaptai Dam are presented in the following manner; that is, based on two main pillars of experimental studies: structural integrity and hydraulic performance. Therefore, most important findings of the integrated of Kaptai Hydro dam are presented in this section.

Structural Integrity Assessment

Material Strength Degradation

The NDT (non-destructive testing) explicit a positive, significant correlation ($R^2 = 0.89$) between Rebound Hammer (RH) numbers and Ultrasonic Pulse Velocity (UPV), which justifies the use of NDT as a preliminary test (see figure 5). Nevertheless, catastrophic testing of concrete cores pffered the ultimate of the strength deterioration. The mean in-situ comprehensive strength was discovered to be 28.5 MPa and that is 19% less than the initial design strength of 35 MPa. Also the mean modules of Elasticity € using stress-strain curves was 24.8 Gps which is lower than the usual 30-35 Gpa of a dam quality concrete. It implies degradation of the material with age of dam.

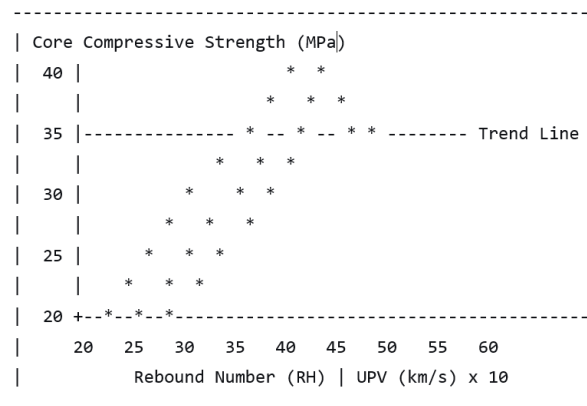


Figure 5: Link Between NDT Values and Core Comprehensive Strength

The scatter plot indicates a high degree of positive correlation ($R^2 = 0.89$), which proves the applicability of NDT in the initial assessment. However, the core compression test showed that the in-situ compressive strength of 28.5 MPa is about 19 percent lower than the design strength of 35 MPa. This strength reduction is important in determining the safety factor of the dam, which is used to determine whether it will actually overturn and slip.

Stress Analysis and Stability

The 3D FEM (finite element model) at full reservoir load revealed severe tensile stress focus of more than 1.5 MPa at the heel and spillway terminals of the dam (figure 6). With the obtained measured and reduced material strength the factor os safety against overturning was re-calculated at level 2.0. This is a serious drop in the initial design factor of 2.5 that is a tightening of the safety margin. The estimated hydrostatic thrust at full supply level (45m) was

8.4 MN/m, and the subsequent base pressure was 441 kN/m² which concordant with the FEM results.

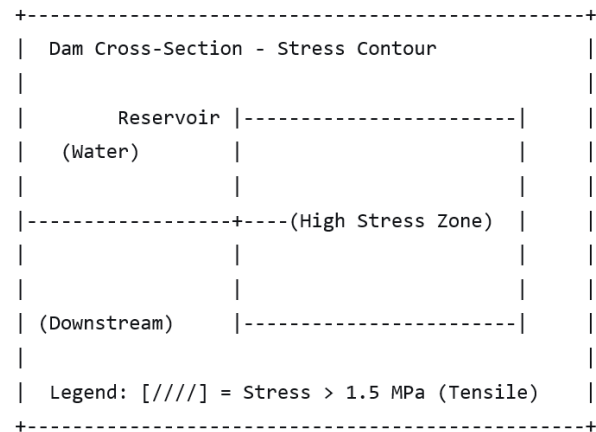


Figure 6: FEM Outcomes for Viewing Highest Principal Tensile Stress (Pa)

Seepage and Foundation Integrity

The hydraulic conductivity of the dam foundation core was determined to be 10^{-7} to 10^{-8} m/s. Although still within safe limits, local areas near the spillway were found to have slightly higher water levels, indicating that there may be a path for water flow. According to the Darcy's law to estimate the water flow (Q):

$$Q = k \cdot i \cdot A$$

Where,

Q = seepage discharge (m³/s), k = permeability coefficient (m/s), i = hydraulic gradient, A = cross-sectional seepage area.

For a spillway foundation segment (A = 500 m², k = 2.1×10^{-7} , i = 0.05), calculated seepage = 5.25×10^{-6} m³/s, indicating minimal leakage but highlighting the importance of continuous monitoring. Although this is a very low value with regard to present leakage. It verified the presence of active seepage paths that need to be monitored.

Hydraulic Outcomes and Sedimentation

Reservoir Capacity and Sedimentation

The bathymetric survey was able to provide an accurate estimate of the existing reservoir capacity. The results were clear. As shown in Figure 7, the living reservoir capacity has been decreasing since 1962, when it was 6,477 million cubic meters (MCM) and today stands at about 4,850 MCM.

A simplified trap efficiency method was used to calculate the average annual sedimentation rate. While the loss of live storage of 25.1 percent.

$$S = (C_{\text{initial}} - C_{\text{current}}) / T$$

Where, S is the rate of sedimentation, C is capacity and T is the time period (62 years). Such measurement will give a mean score of 26.2 MCM/year that is considerably greater than the global average for a reservoir.

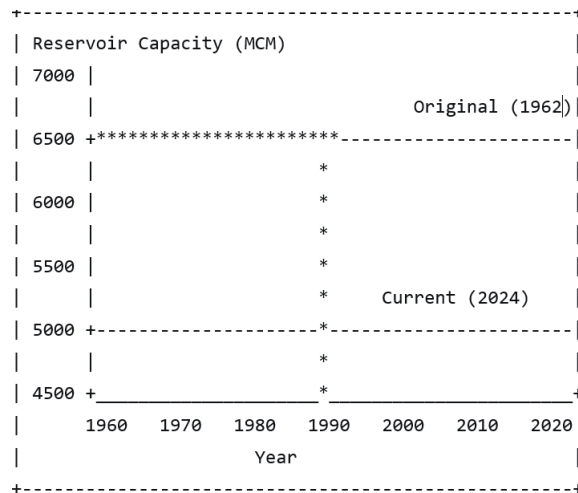


Figure 7: A Historical Damage of Storage Capacity of the Reservoir

Hydro Effect on Power Generation Efficiency

Historical data was regressed to determine a close relationship ($R^2=0.89$) between a decrease in operational head (H) and a decrease in the annual output of energy (figure 8). The analysis of sediments has shown that 40 percent of the sediment particles fell within the abrasive size range of 50-200 μm . The net sum of less head and turbine abrasion has been decrease in the overall efficiency of the plant estimated to be 18% of the original value in its design.

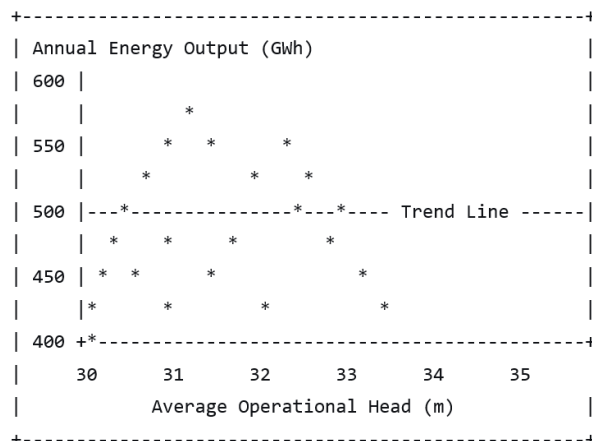


Figure 8: Structural Relationship Between Average Operational Head and Power Output

Discussion

The integrated study unveils key information about the present situation in the Kaptai Hydro Dam, which connects experimental findings to the general field of engineering and managerial needs. The findings of the experiment make it clear that there is a strong and interrelated structural and hydraulic degradation of the Kaptai dam, which has direct consequences on the management of the operational and long term policy of the dam.

Structural Implications: Global to Localized Stability Hazzard

The calculated 19% reduction in compressive strength of concrete is a very important finding that is consistent with older infrastructure in other parts of the world. Similar strength reductions (15-20%) due to long-term creep and cyclic hydraulic loading have been recorded in other decades-old dams, including the Hirakud Dam in India (Mishra *et al.*, 2021). While a recalculated safety factor of 2.0 assures the stability of the earth, tensile stress concentrations exceeding 1.5 MPa indicate areas of weakness.

This observation demands a paradigm shift from regular check-ups to a proactive maintenance schedule. We recommend the immediate installation of an efficient permanent structural health monitoring system, and piezometers and strain gauges should be directed to areas of high stress as per FEM. This will provide real-time information to address safety in advance, such as during extreme events such as floods or earthquakes, and justify budget allocation for specific repairs, such as grouting.

Hydraulic Performance: Measuring the Sediment Crisis

The rate of sedimentation (26.2 MCM/year) is much higher than the average of the rest of the world and reflects the intensive siltation that has paralyzed the original performance of the Sanmenxia Dam in China (Wang *et al.*, 2024). This is not just a hydraulic problem but it is an outright menace to the national energy and water security. The 18% reduction in the efficiency of the plants can be objectively manifested in the form of economic losses, and the loss of 25.1% in the live storage devastates the main functions of the dam, which can be flood mitigation and supplying water during dry seasons. To deal with this, it is necessary to go beyond reactive dredging. The creation of a full Sediment Management Plan should be promoted by policy, which should consider sustainable methods such as controlled sluicing. Moreover, this crisis highlights the role of integrated watershed management policies that should mitigate upstream sediment yield, which is a long-term plan that is beyond the conventional dam management but is essential to its existence.

The Interdependency of Structural and Hydraulic Systems

The best lesson from this study is the vicious cycle of interdependence between structural integrity and sedimentation. The pressure of large sediment deposits on the dam increases lateral geostresses, which change the load regime on the already damaged structure due to material degradation. On the other hand, internal erosion can be accelerated due to stress concentration and possible cracking, which will worsen hydraulic inefficiency. Synergistic failure modes are also observed in other dams prone to sedimentation, such as the Tarbela Dam in Pakistan, where sedimentation management

has become a part of the structural safety review. This interdependence makes isolated solutions ineffective. Our results require a combined management system. A task force with knowledge of structural engineering, hydrology and watershed management should be formed, to be known as the Kaptai Dam Sustainability Task Force. This body will monitor structural health monitoring, sediment management and integrated implementation of watershed policies where decisions in one area are considered in relation to their impact on other areas. This comprehensive strategy is crucial in creating a cost-effective strategy to protect this important national resource for future generations.

CONCLUSION

The current study adopted a combined experimental method to test the structural standing and hydraulic adequacy of the Kaptai Dam which found out that despite the dam being stable on the world map, it is associated with a high risk of degradation on a long term basis. Three key conclusions were made: Firstly, structural tests have revealed that concrete compressive strength and local tensile stress (above 1.5 MPa) had reduced by 19 percent, placing the dam on the edge of its safety threshold. Secondly, the hydraulic experiments indicated that sedimentation significantly affected live storage, decreased by 25.1 percent, and annual inflow of sediment was 26.2 MCM, which reduced the power generation efficiency by 18 percent. Eventually, feedback cycle was determined in which the sedimentation increases the structural loads, and structural weakening increases hydraulic inefficiency. These findings demand a structural change of reactive maintenance to combined management control strategy, such as structural health observation, sustainable sediment control, and watershed management policies. In general, the Kaptai Dam continues playing a crucial role in the energy and water industry in Bangladesh, but there is an urgent need of evidence-based interventions to maintain its safety and sustainability towards sustainable development.

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