Monitoring the Deformation Pattern of an Instrumented Concrete Arch Dam

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ABSTRACT

Structural Health Monitoring (SHM) and prognosis could play a crucial role in the life cycle of a critical infrastructure such as a large dam. Such monitoring practices serve multiple functions and are essential components in ensuring the safety and effective maintenance of such structures. By providing insights into a structure's behaviour, structural health monitoring assists in calibrating numerical models and complements visual inspections. This process facilitates informed decision-making, aids in planning maintenance and rehabilitation schedules, and ensures the desired safety of the structure throughout its lifespan. This paper presents a case study of a double curvature large thin concrete arch dam that is currently experiencing slow irreversible upstream movement of the central dam crest. The dam is well-instrumented, with instrumentation falling into categories such as hydro-metrological, geotechnical, geodetic, and seismic monitoring. The primary objective of this paper is to validate and establish a level of confidence in numerical modelling by comparing the displacement of an instrumented concrete arch dam with the with that calculated from its finite element method (FEM) model. To achieve this, a sequential thermo-mechanical analysis was performed on a 3D model of the dam foundation reservoir system. Additionally, the study utilizes a well-known statistical model called Hydrostatic-Season-Time (HST) model, based on multi-linear regression analysis, to predict the dam's future displacement using the relevant data from the sensors placed in the dam. The findings indicate a good correlation between the observed dam displacement based on instrumentation data with that calculated from the Finite Element Analysis (FEA) considering the presence of vertical joints. Moreover, the HST model proves to be a suitable choice as it closely matches the observed data and demonstrates good predictive capabilities for future dam behaviour and helps isolate the effects of different parameters on the dam displacement.

Key words: Structural Health Monitoring (SHM), Concrete Arch dam, finite element method (FEM), arch dam, thermo-mechanical analysis, Hydrostatic-Season-Time (HST) model, Decision support system

INTRODUCTION

Critical civil infrastructure such as large dams require significant investment. They are essential for economic stability, but they are prone to deterioration due to factors like aging, improper operation, and insufficient maintenance. These dams pose risks to downstream communities, property, and the environment during extreme natural events like earthquakes and floods, emphasizing the need for their ability to withstand such events without substantial damage [1]. Therefore, conducting a comprehensive assessment to evaluate their vulnerability to these hazards is crucial.

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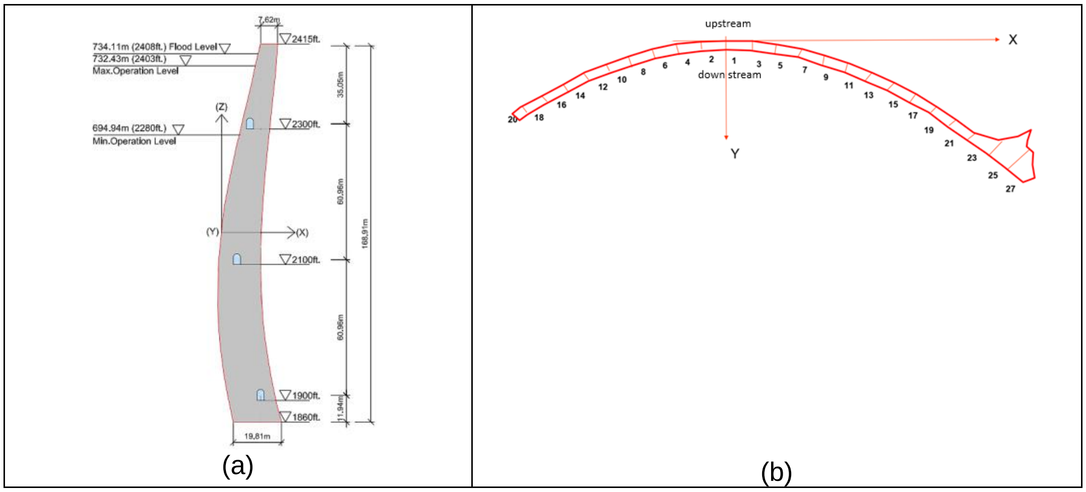
Additionally, the aging materials of the dams are susceptible to adverse weather conditions that can weaken their strength and operational performance, making a thorough safety evaluation necessary to ensure expected functionality. This evaluation entails a comprehensive approach, including expert site visits, material analysis, instrumentation data scrutiny, and numerical simulation. Moreover, it is essential to consider changes in the operational environment, hazard levels, such as floods and seismic events, and the desired performance of the structures to ensure their resilience and long-term sustainability [2]. The safety assessment of dams encompasses various disciplines, including hydro-mechanical, structural, and geotechnical aspects. The dam studied in this case is a large, double curvature, thin arch dam that was constructed in the seventies. The dam exhibited continuous upstream deflection since the beginning of eighties, accompanied by indications of minor distress [3].

A comprehensive safety assessment was undertaken which includes, interpretation of the instrumentation data, development and analysis of a 3-D numerical model of the Dam Foundation and Reservoir (DFR) system, and material investigation to find out the plausible reasons for the observed behaviour of the dam. This paper focuses on two specific safety assessment aspects: conducting a sequential thermo-mechanical analysis through 3D numerical simulation and performing a statistical analysis of the dam from the instrumentation data using a data driven model. The main objective is to establish the validity and a level of a confidence in the numerical model by comparing the observed behaviour of the dam from the instrumentation system with the results obtained from the finite element method (FEM) model of the dam. To accomplish this, a sequential thermo-mechanical analysis is conducted on a 3D dam foundation reservoir (DFR) model. Additionally, the study employs the Hydrostatic-Season-Time (HST) model [10], which utilizes multi-linear regression using the training data, to predict the future displacement. The results reveal that there is a correlation between the observed dam behaviour, as indicated by the instrumentation data, and the displacement calculated using the Finite Element Analysis (FEA), with improved accuracy when accounting for the presence of vertical joints. Additionally, the HST model proves to be an appropriate selection as it closely aligns with the observed data and exhibits reliable predictive capabilities for forecasting future dam behaviour.

Case study dam and the unusual Behaviour

The arch dam considered here has an asymmetric shape with a total of 24 blocks, consisting of 10 monoliths on the right side (even-numbered) and 14 monoliths on the left side (odd-numbered). At its central cantilever, the dam has a height of 168.91 m, while the length of the dam at its crest measures 365.76 m. The width of the dam at the crest is 7.62 m, and it widens to 19.81 m at the deepest foundation level. The dam is equipped with three galleries positioned at the depths of 35.05 m, 96.01 m, and 227.07 m from the crest elevation. The first filling of the reservoir to its full level was carried out in 1981. The dam exhibited continuous upstream deflection since the beginning of 1982, accompanied by indications of minor distress. The central crest of the dam studied in this case has been undergoing a gradual and irreversible upstream movement. Over a period of 32 years, the dam has experienced an average-



(a)

(b)

Figure 1. (a) cross section central block (b) block layout of dam

annual displacement rate of 1.30 mm. Notably, the most significant movement occurred between 2013 and 2014, reaching 41.7 mm based on pendulum data. However, it is important to consider that adjustments for the pendulums' late baseline readings suggest that the actual upstream movement of the dam during the study period may be slightly lower than that observed. Similarly, the upper reach of the dam's central region also displays an irreversible upheaval, with a maximum vertical movement of 22 mm and an average annual displacement rate of 1.16 mm over a period of 19 years [4,5,6]. The vertical cross section of the central block and the horizontal layout of the dam are shown in Figure 1 (a) and (b) respectively. Other physical parameters and material properties are presented in Tables I to III.

Finite Element Analysis of Arch Dam

A 3D DFR finite element model developed in Abaqus to analyse the behaviour of the case-study dam under thermo-static conditions. The 3D model was divided into separate components, namely the concrete dam, reservoir, and the deformable rock mass (Figure 2). The concrete material was assumed to follow linear elasticity, justified by evaluating the maximum principal stresses within the dam body which remained below the limit of proportionality. The rock mass was modelled using the Mohr-Coulomb failure criterion to account for plasticity. Material properties are detailed in subsequent tables. Cohesive interaction was assigned to block joints to allow the joint openings and closing, while relative sliding was restricted. Similarly, contact interactions were employed to model the interaction between the dam and its foundation, constraining relative sliding but allowing for separation. The analysis carried out in Abaqus standard. All dam blocks, the rock foundation, and abutments were meshed with C3D10I structural elements for capturing the static behaviour. Similarly, for thermal analysis of dam body DC3D10 element, was used. After conducting the heat transfer analysis, the thermal stresses were computed and integrated into the structural model [3,4]. The temperature boundary conditions for various water levels and ambient temperatures are depicted in the accompanying Figure 3.

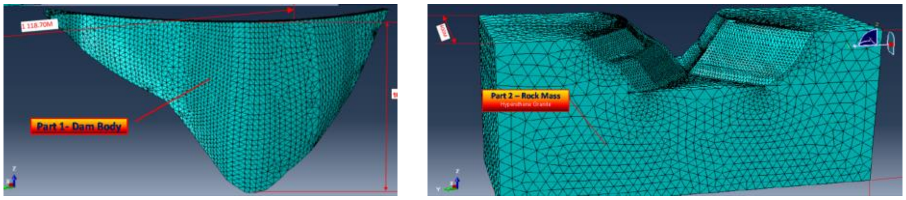
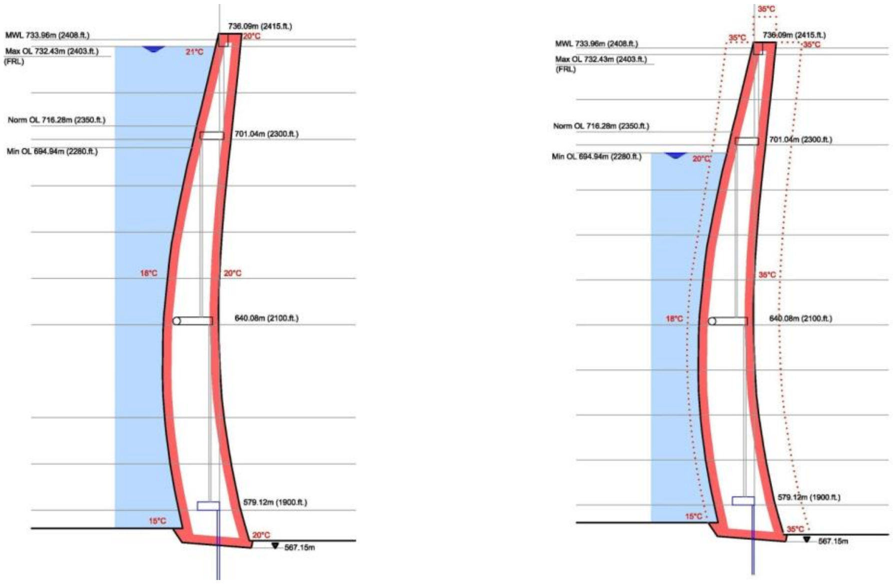


Figure 2. Finite Element Model of (a) Dam body (b) Foundation



(a) (b)

Figure 3. (a) Temperature Loads allocated to heat transfer dam models for FRL and minimum ambient temperature
(b) Temperature Loads allocated to heat transfer dam models for MWL and maximum ambient temperature

TABLE I. THE DETAILS OF MATERIAL PROPERTIES CONSIDERED FOR FINITE ELEMENT METHOD STUDY USING ABAQUS.

Description	**Adopted for this Study**
Volumetric Weight, dry density of concrete, **γ**	0.0245 MN/m^3
Compressive Strength of intact concrete material, f_c'	40 MPa
Tensile Strength of intact concrete material, f_t	2.9 MPa
Tensile Strength of rock mass - concrete joints, f_{tj}	0.0
Creeping of the Concrete: Creeping stresses level after which the concrete is expected to start creeping.	16 MPa (0.4*40 MPa)
Sustained Modulus of Elasticity **E**	25 000 MPa
Poisson Ratio of Concrete Material **μ**	0.25
Shear Strength of intact concrete material **C**	4.0 MPa
Remaining shrinkage of concrete	$0.156*10^{-3}$
	$0.59*10^{-4}$

TABLE II. THERMAL PROPERTIES OF CONCRETE

Coefficient of Thermal Expansion	**Thermal Conductivity**	**Specific Heat**	**Thermal Diffusivity**
10.7 x 10-06 /^{0}C	2.65 [W/m^{0}C]	1 kJ/Kg^{0}C	0.0040m^{2}/h

TABLE III. PHYSICAL AND MECHANICAL PROPERTIES OF ROCK MASS

Description	***Foundation***
Volumetric Weight (γ)	0.025 MN/m^{3}
Modulus of Elasticity (Deformability) (E)	21 000 MPa
Poisson Ratio (μ)	0.20
Tensile Strength	1.5 MPa
Cohesion (C), Peak value	2.5 MPa
Angle of internal friction (f), peak value	45^{0}

RESULTS AND DISCUSSIONS OF FEM ANALYSIS

For this study, discontinuous models with galleries have been considered which simulates dam-foundation interaction, dam block interaction. Following conditions were considered in the FEM analysis.

a. Minimum Operation level of the reservoir, 2280 ft, associated with Maximum concrete temperatures
b. Minimum Operation level of the reservoir, 2280 ft, associated with Minimum concrete temperatures
c. Maximum Operation level of the reservoir, 2408 ft, associated with Maximum concrete temperatures
d. Maximum Operation level of the reservoir, 2408 ft, associated with Minimum concrete temperatures

First, heat transfer analysis was performed based on the above water level and ambient temperature conditions and the temperatures are then mapped onto the structural model. Structural loads include gravity, hydrostatic and thermal stresses due to thermal expansion. Following TABLE III shows the correlation obtained between the instrumentation data and the results obtained from FEA model.

TABLE IV. THE INSTRUMENTATION DATA AND THE RESULTS OBTAINED FROM FEA MODEL

Block No. & Height	Total Duration	Pendulum Monitoring 1975-1981 (82)			Collimation Monitoring 1977-81 (82)			Max. Deformation as per 3D model, load case (18), 05-B, [max WL, T max & D/S Radiation]
		Max U/S deflection of crest (mm)	Average		Max U/S deflection of crest (mm)	Average		
			per year (mm per year)	per m of height (mm per m)		per year (mm per year)	per m of height (mm per m)	
Block 1 (168.9 m)	Max 32 years 1981-82 to 2013-14	U/S-41.5 (2013-14)	1.30	0.246	U/S-26.0 (2013-14)	0.81	0.154	U/S-34.88 mm
Block 7 (119.08 m)		U/S-41.7 (2013-14)	1.30	0.350	U/S-22.5 (2013-14)	0.70	0.189	U/S-34.88 mm
Block 8 (144.44 m)		U/S-30.3 (2013-14)	0.95	0.265	U/S-13.3 (2013-14)	0.42	0.116	U/S-27.80 mm

Data-driven Model: Hydrostatic-Season-Time (HST)

A data driven statistical techniques for dam monitoring, Hydrostatic-Season-Time (HST) model was utilized here to analyze and predict the behavior of the dam over time. This model incorporates various factors, including hydrostatic pressures, seasonal variations, and temperature effects, to provide a comprehensive understanding of dam response [7]. A brief description of this model is provided here. The HST model was originally developed at the Electricity de France [3], It captures the long-term response of dams by accounting for the time-dependent nature of hydrostatic loads. The HST model has been extensively applied in dam engineering. For instance, researchers utilized the HST model to analyze the deformation behavior of dams and evaluate safety [4,10].

This monitoring model plays a crucial role in dam engineering, enabling engineers and researchers to assess the performance and safety of dams under various loading conditions. By considering the effects of hydrostatic pressures, seasonal variations, temperature changes, and the passage of time, these models provide valuable insights into the behavior and response of dams, aiding in decision-making processes related to dam design, maintenance, and safety. This paper utilizes the HST model to analysis and predict the future performance of a case study arch dam.

The basic Hydrostatic-Season-Time (HST) model represents the displacement of a dam as a combination of three factors: hydrostatic conditions (reservoir level effects), seasonal effects, and irreversible effects (time drift). In the HST model, the displacement at time t, denoted as M(z, τ, t), is determined by the superposition of the following components: a constant term A_0 representing the bias, the response H(z) due to hydrostatic load, the response S(τ) due to the seasonal effect, and the effect T(t) of time or irreversible drift. The HST model does not explicitly consider the effect of temperature; however, the temperature effect is implicitly incorporated within the seasonal parameter S(τ) [3,10]. The H, S, and T functions in the HST model are represented as follows:

$$M(z,\tau,t) = A_0 + H(z) + S(t) + T(t) \tag{1}$$

$$H(z) = a_1 z + a_2 z^2 + a_3 z^3 \tag{2(a)}$$

$$S(\tau) = \ b_1 \sin(\omega\tau) + \ b_2 \cos(\omega\tau) + b_3\, sin^2(\omega\tau) + b_4\ \sin(\omega\tau)\cos(\omega\tau) \tag{2(b)}$$

$$T(t) = c_1 t \tag{2(c)}$$

In the HST model, the hydrostatic response function H(z) is represented by a cubic polynomial of the hydrostatic head. This polynomial captures the relationship between the displacement and the hydrostatic load applied to the dam. The seasonal response function S(τ) is represented by a sum of four sine functions of ω, where ω = 2π / 365. The variable τ represents the i^{th} day in a year, and the sine functions account for the cyclic variations observed due to seasonal effects. The time response function T(t) is represented in terms of a monotonic time function. This function captures the irreversible drift or time-dependent behavior of the dam over long-term periods. By combining these components, the HST model provides a comprehensive representation of the displacement behavior of the dam, incorporating the effects of hydrostatic conditions, seasonal variations, and irreversible drift over time.

HST MODEL RESULTS AND DISCUSSION:

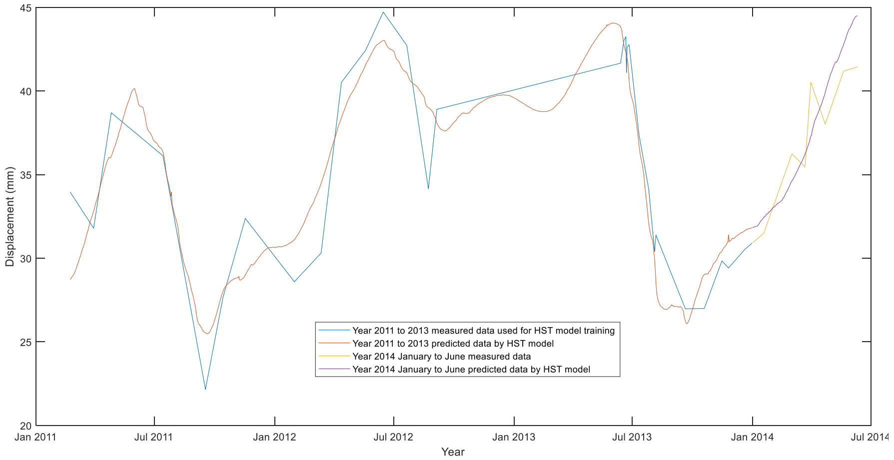


Figure 4. Pendulum Displacement data of Block 1 (Training data and Predicted data)

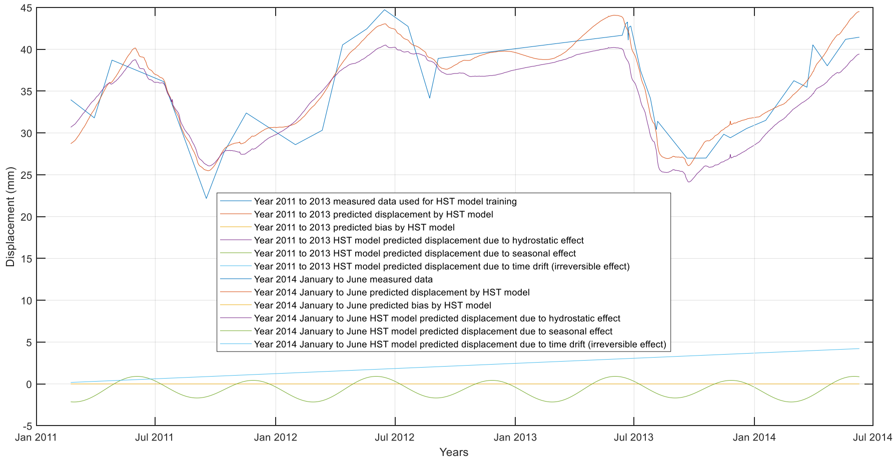


Figure 5. Pendulum Displacement data of Block 1 by HST model prediction for 2011 to 2013 and six months of year 2014 (Total and Individual components)

In the analysis, pendulum displacement data for 3 years (2010-2013) for Block 1 of the dam has been used to train the HST model parameters and to evaluate the unknown parameters of the model. After that, the values of displacement for the year 2014 (months January to June) has been predicted and compared as shown in Figure 3. Finally, the four displacement components have been separated and plotted in Figure 4. It is observed from Figure 4 that the hydrostatic component of displacement is maximum.

CONCLUSION

A finite element model of the dam-reservoir foundation system of a concrete arch dam analyzed for thermal stress induced deformation show that the dam temperature variation produces significant deformation, which is consistent with the observation. The results predicted by HST model provide a comprehensive view of the observed values. These findings highlight the importance of monitoring, the use of complementary instrumentation techniques, numerical simulation and data driven techniques in understanding the behavior of dams, particularly when abnormal or unexpected movements are observed. The HST model also allows for separating the influence of hydrostatic pressure, season, and time on the dam displacement. It is observed from the results that the hydrostatic pressure has the primary contribution to the displacement, and the time effect shows a steady and ongoing long-term displacement.

While the data-driven analysis presented in this case study has its merits, it has limitations in terms of providing detailed information about trends and potential anomalies in the data. To gain a more comprehensive understanding of the damage state and vulnerability of the dam, a detailed physics-based analysis using a finite element model of the structure or use of improved models such as HSTT, HTT may be necessary [10]. This type of analysis considers the intricate interactions between various structural components, providing a more complete picture of the dam's behavior and potential risks.

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