Scientific Paper

Time-Dependent Deformation of a Concrete Arch Dam in Thailand - Numerical Study on Effect of Alkali Silica Reaction on Deflection of Arch

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Abstract

A detailed inspection of a dam in Thailand is reported for its time-dependent gradual expansion towards upstream, contrary to the expected downstream creep deflection owing to hydrostatic loads. In this study, based on petrographic analysis and SEM, a sample of cored concrete from the dam was found to undergo a low to moderate level of ASR. The potential for future expansion was verified using an accelerated laboratory test. The experimental data were used to evaluate the dam performance by conducting an FEM analysis. The numerical model was calibrated with the observed deflection, and the mechanical stresses owing to the combined ASR and hydrostatic loads were estimated for various ages of the dam. In addition, stress and deflection were predicted using probabilistic methods. A sensitivity analysis was also performed to monitor the behaviour of the dam under various environmental conditions and input parameters. It was found that the gradual deterioration by ASR does not pose a high risk to the dam under normal loading conditions.

1. Introduction

Dams are vital infrastructures because of their multiple purposes, such as flood control, irrigation, power generation, and potable water supply. Any deleterious effect on a dam can result in operational problems, including obstruction of sluice gates, displacement of foundation, deflection of conduits, overstressing of embedded parts, and misalignment of machinery. If they are not corrected, a stoppage of services is possible. Thus, monitoring and evaluating the serviceability and safety of dam have a great economic and social importance.

Most of the current study on dam safety is focused on earthquake related risks. Although a sudden dam failure would be catastrophic, it must be noted that large dams are designed to withstand earthquakes with a return period of 10,000 years which means dam failure due to earthquake alone has very small likelihood (Wieland 2010). In the other hand, many dams have undergone some kind of durability problem such as displacement and cracking (Blanco et al. 2019; Dolen et al. 2003). Diagnosis method proposed by Balanco et al. is useful to systematically identify durability problem in dams. Neglecting such deterioration process may result in unfavourable situations. In some cases, the deteriorated dams have to be decommissioned for safety reasons, such as the Stolsvatn dam in Norway (Sellier et al. 2017).

One of the concrete dams in Thailand operated for 55 years needed to verify its safety as it recently started showing unaccounted deflection, which is increasing gradually over time. The dam is arch dam and was constructed in 1964. It is 154 m high at the tallest section and 486 m wide at the crest level. The water impounded by the dam is used for irrigation and generating electricity. The location of the dam is shown in Fig. 1.

Here, the aim is to study the diagnosis of the time-
dependent deflection and its future performance by conducting a numerical analysis. The methodology shown in this paper can be applied to any other similarly affected dams.

2. Diagnosis of the problem

The deflection of the dam was measured using a plumb line. Figure 2 shows the location of deflection measuring device. The device is installed in block 12 at the centre of dam body. As shown in Fig. 3(a), the deflection gradually increases in the upstream direction. In an arch dam, the expected behaviour is that the radial deflection occurs in the downstream direction for normal hydrostatic loadings (Ghanaat 1993). Even when concrete creep is considered, the deflection should increase in the downstream direction (Yin et al. 2019). The effect of creep should be small because the dam concrete uses a large volume of large-sized aggregates to reduce hydration heat, and the relative humidity remains stable (Neville 1996). However, the observed deflection is opposite to the expected direction.

For deflection to occur in the upstream direction, one of the possible mechanisms is an expansion of the dam concrete. The expansion can push the concrete in all directions owing to an increase in volume; however, because of the arch geometry of the dam, the deflection towards the downstream is restricted, and thus, the dam deflects in the upstream direction, as shown in Fig. 3(b).

One of the phenomena causing expansion is temperature rise. Thermal expansion due to the ambient temperature rise is not monotonic, which means that the expansion should be recovered when the temperature drops. However, such a monotonic temperature rise has not been reported in Thailand. The maximum thermal expansion should become stable after approximately three thermal cycles (Roth and Dolice 2017) by the opening of cracks. Furthermore, in the case of the target dam, thermal cracks have not been detected on the dam surface (Bui et al. 2019). Thus, the gradual expansion owing to temperature fluctuation can be ignored.

Another expansive phenomenon is swelling owing to water absorption. In the case of an arch dam with a massive concrete body, the moisture content can remain uniform throughout its body except at the outer face, whose thickness can be neglected with respect to the overall size of the structure (Steffens et al. 2003). Therefore, the possibility of expansion owing to moisture variability is low. Conversely, deflection decreases when the water level rises (Fig. 3(a)), even though increased moisture absorption should lead to a higher deflection. Thus, this mechanism can be disregarded.

Chemical reaction is another possible expansive mechanism, causing an increase in volume. Considering the hot tropical climate of Thailand (Fig. 1), the possibility of temperature rise owing to mass concreting and easy availability of moisture in the hardened phase, Delayed Ettringite Formation (DEF) can be suspected (Bouzabata et al. 2012). Aggregate in Thailand also has the potential for the Alkali Silica Reaction (ASR) (Yamada et al. 2013; Sujjavanich et al. 2017), and has been reported in highway bridges (Sujjavanich et al. 2012);
however, ASR in the dams has not been reported often in Thailand. To check if the dam is affected by DEF or ASR, core samples were extracted from the dam: one from a depth of 0.00–0.300 m (C1) and another from a depth of 0.70–1.00 m (C2) near the right abutment.

2.1 Petrographic analysis
A petrographic analysis was carried out to identify the constituent minerals and examine the possibility of ASR and DEF. The cutting surface was observed using a stereoscopic microscope to identify the fine and coarse aggregates, aggregate geometry, and ASR gel. Polished thin sections (20 × 30 mm, thickness of about 15 μm) were prepared for polarizing microscopy to identify the rock types, sites of reactions, and the extent and sequence of ASR in concrete mineral types based on the previous studies (Godart et al. 2013). Figure 4 shows the cutting surface of C1 sample, and Figs. 5 and 6 show the magnified surfaces. Similarly, Fig. 7 shows the cutting surface of C2 sample, and the magnified surfaces are shown in Figs. 8 and 9. The rock types of both fine and coarse aggregates were identified to be gneiss. In both core samples C1 and C2, the seepage of ASR gel was found around the aggregate. Figure 10 shows the polarizing microscopic observation of coarse aggregates in C2 specimen. The C1 specimen had a similar tendency in the aggregate. As shown in Fig. 10, the gneiss in the coarse and fine aggregate with ASR gel originates from calcareous to politic/arenaceous types in both C1 and C2 samples, which mainly consist of calcite, dolomite, quartz, microcrystalline-cryptocrystalline quartz, muscovite, biotite, plagioclase, potash-feldspar, tremolite, and diopside. Fine cracks in the coarse aggregate of politic/arenaceous gneiss were found with the filling ASR gel products, as shown in Fig. 10.

To confirm the products in the crack, the results observed by SEM-EDS are shown in Fig. 11. The products consist of mainly Si with Ca, Na, and K, which are identified as typical ASR gel products. This indicates that the microcrystalline-cryptocrystalline quartz reacts with alkali in the cement to precipitate the ASR gel. However, the deterioration grade can be evaluated as weak or moderate, corresponding to the cryptic or developing stage according to the definition of previous studies (Katayama et al. 2004).

Furthermore, when observed under the polarizing microscope, no gaps around the aggregate or surrounding cracks in the cement paste, which are typical characteristics in DEF, were found even in the C2 sample, wherein a large hydration heat would be generated at a greater depth (Wang et al. 2019). Hence, the possibility of DEF is low according to the petrographic analysis.

2.2 Residual expansion test
Cylindrical concrete core samples of 10 cm diameter were used for the residual expansion test. The samples were conditioned in water at 20°C until they were com-
pletely saturated, and expansion became stable. The process took 150 days, and the strain was 0.045% and 0.035% for C1 and C2, respectively. At this point, the zero reading was set, and the specimens were submerged in NaOH solution (1 M concentration) at 80°C for the accelerated ASR test.

The expansion of the cores during the accelerated test is shown in Fig. 12. A maximum strain of 0.15% and 0.12% was recorded for core samples C1 and C2, respectively, at the age of approximately 90 days. Specimen C1 extracted near the surface (0.0–0.3 m) has a larger potential for expansion compared to Specimen C2 (0.7–1.0 m). It can be suggested that C2 had experienced a high temperature owing to the heat of hydration at a deep depth that can accelerate ASR during early service life, and thus, causing a small residual expansion. It is believed that without the high-temperature incidence, C1 near the dam surface exhibits a lower ASR than C2. The difference in the residual expansion between C1 and C2 is small.

This test indicated that both core samples have a residual ASR expansion potential. According to the ASTM C1260 guidelines (mortar bar test), an expansion between 0.1% and 0.2% in 16 days indicates that the specimen has ASR potential. Because specimens C1 and C2 are concrete specimens, this test does not entirely conform to ASTM; nonetheless, similar accelerated tests performed by other authors, such as Kuroda et al. (2008) and Thomas et al. (2008), have shown that this method also can predict the potential ASR expansion.
3. Numerical analysis for time-dependent deformation in a massive dam

The simple method to perform numerical analysis of ASR affected structure is by applying an equivalent thermal load to emulate the ASR strain, as done by Larsen et al. (2008). Such models are inflexible and cannot incorporate the thermo-chemical variation. The numerical modelling of ASR used in this study is based on thermo-chemo-mechanics proposed by Ulm et al. (2000), which was originally based on Larive (1998). This method incorporates environmental parameters, such as temperature, start time, and duration of the reaction, and provides a convenient method for model calibration. This model has been used by various authors in their analysis, such as that of Kleinplaas Dam by Pourbehi and Zijl (2019) and Kariba dam by Pan et al. (2013). Saouma et al. (2007) showed that the stress distribution can be captured correctly using this model in a parametric study.

In this study, the numerical model was implemented in an open-source finite element software, Code_Aster, which has the capability of coupled analysis of thermal, mechanical, and acoustic behaviours (Code_Aster 2017). A three-dimensional model was used. The mesh size of the model was optimized by sensitivity analysis. Once the mesh size was fixed, thermal analysis was performed using Equation 1. The temperature distribution from the thermal analysis was used to calculate the latency and characteristic time for each element inside the dam body. The free strain and stress were calculated based on Equations 2 to 8. The stress field was applied to the model, and mechanical analysis was performed.

Since cracks have not been observed on the dam surface, linear analysis was used. The possible restraint effect due to reinforcement has not been incorporated because the percentage of reinforcement is low for mass concrete of dam. The numerical analysis was run multiple times to calibrate the observed deflections.

3.1 Model description

(1) Thermal modelling

The temperature distribution inside the dam can be determined using Equation 1.

$$\frac{\partial(\theta - \theta_o)}{\partial t} = D_\theta \text{div} \{\text{grad}(\theta - \theta_o)\}$$  \hspace{1cm} (1)

where $D_\theta = K/C$ is the thermal diffusivity, $K$ is the thermal conductivity, $C$ is the heat capacity of concrete, $\theta$ is the actual temperature, and $\theta_o$ is the reference temperature.

The boundary conditions (i.e., the surface temperature) of the dam will be in equilibrium with the air or water temperature immediately near it, while the inner core temperature will depend on the thermal properties of the concrete.

(2) Strain evolution due to ASR

The reaction rate of ASR at any time ‘t’ is provided by Equation 2, based on the model proposed by Ulm et al. (2000).

$\text{Expansion} = \text{Characteristic time} \times \text{Stress field}$
where \( \tau_c \) and \( \tau_L \) are the characteristics and latency times, respectively, as shown in Fig. 13. Physically, the latency time is the duration required for nucleation, initiation of reaction and partial acceleration of reaction while the characteristics time is the duration during which the reaction is accelerated and concrete starts deteriorating rapidly (Saouma et al. 2015). The characteristics and latency period depend on the actual temperature \( \theta \) and the reference temperature \( \theta_0 \) as follows:

\[
\tau_c(\theta) = \tau_c(\theta_0) e^{\left(\frac{U_c}{\theta} - \frac{U_c}{\theta_0}\right)}
\]

(3)

\[
\tau_L(\theta) = \tau_L(\theta_0) e^{\left(\frac{U_L}{\theta} - \frac{U_L}{\theta_0}\right)}
\]

(4)

where \( U_c \) and \( U_L \) are activation energies obtained by

\[
U_c = 5400 \pm 500K, \quad U_L = 9400 \pm 500K
\]

(5)

and \( \tau_c(\theta_0) \) and \( \tau_L(\theta_0) \) are basic lag time and characteristic times, respectively.

The reaction rate should be integrated over time to obtain the total reaction. The stress-free expansion owing to ASR is calculated by multiplying with the maximum possible strain \( \varepsilon(\infty) \).

\[
\varepsilon(t) = \varepsilon(\infty) \ast \xi(t)
\]

(6)

From Equations 3 and 4, the ASR increases exponentially with temperature following the Arrhenius equation (Alnaggar et al. 2013); thus, ASR is more vulnerable to tropical climatic zones, such as Thailand.

The lag time \( \tau_c \) and characteristic time \( \tau_L \) control the rate of strain evolution. The age at which ASR manifests can fluctuate significantly. ASR is slow in the case of large dams and can assume an appreciable amount of time until it becomes apparent that the expansion has occurred. It takes even long time to manifest this expansion into serious damage. A summary of the age of the dam at which the ASR was identified is shown in Fig. 14 which is based on data of 40 dams around the world collected by Charlwood and Sims (2016) and Sellier et al. (2017). The mean is approximately 30.8 years, and the standard deviation is 14.3 years. In the case of the target dam, the ASR evolution is still slow, as will be discussed in the calibration section.

### (3) Modulus of elasticity

The deterioration of elastic stiffness \( (E_o) \) by the ASR can be estimated using Equations 7 and 8 (Capra and Sellier 2003).

\[
E = E_o * (1 - d_{asr})
\]

(7)

The ASR damage factor \( d_{asr} \) is a function of the maximum ASR strain at that time, expressed as

\[
d_{asr} = \frac{1 - E}{E_o} = \frac{\max(\varepsilon(t)_{\infty})}{\max(\varepsilon(t)_{\infty}) + B}
\]

(8)

where \( B \) is the calibration parameter approximated to 0.3%.

According to the study by Saouma et al. (2007), the degradation of Young’s modulus has small effect on the long-term deflection. In this study, the difference owing to constant and degrading Young’s modulus was also tested. It was found that a constant, \( E \), can be used without losing accuracy, as will be discussed in the sensitivity analysis.

### 3.2 Model implementation

The parameters of the model can be measured in a laboratory with prescribed tests, such as RILEM TC 191-ARP or ASTM C1260-07 (Lindgård et al. 2012). However, large inconsistencies occur between field measurements and laboratory predictions (Hooton et al. 2013). The inconsistency is mainly owing to the exposure condition and the size of the specimen. Therefore,
the expansion evolution parameters should be suitably modified to be applied in the numerical model.

The first step in the numerical analysis is to determine the temperature distribution in the dam body. The monthly air temperature fluctuation at the dam site from 2014 to 2020 is shown in Fig. 15. Based on this historical data, the average monthly temperature was calculated. The maximum temperature occurs in April (32.1°C) and the minimum temperature in January (24.5°C).

In the thermal analysis, the ambient temperature was applied to the dry surface of the dam. Due to differences in water conductivity, there is a time lag between ambient and water temperatures to gain equilibrium, which results in a low temperature in the reservoir side of the dam during summer and high temperature during winter. However, in this analysis, the time lag was neglected, and the relation between air and water temperature was approximated using \( \theta_{\text{water}} = 0.965 \times \theta_{\text{air}} \), where the temperature is in Kelvin (Stefan and Preud’homme 1993). Other properties are listed in Table 1. The temperature distribution inside the dam body for March, February, and October is shown in Fig. 16; the other months had a similar distribution.

### Table 1 Parameters used for analysis.

| Parameters                              | Values | Unit       |
|----------------------------------------|--------|------------|
| Thermal conductivity of concrete, \( K \) | 1.75   | W/m²/K     |
| Specific heat capacity of concrete, \( C \) | 0.75   | KJ/Kg/K    |
| Thermal expansion coefficient of concrete, \( \alpha \) | \( 10 \times 10^{-6} \) | K/K        |
| \( U_L \)                              | 5400   |            |
| \( U_L \)                              | 9400   |            |
| Initial temperature, \( \theta_0 \)    | 301.41 (28.26) | K (°C)    |
| \( \tau_L(\theta_0) \)                 | 30     | years*     |
| \( \tau_C(\theta_0) \)                 | 60     | years*     |
| Undamaged modulus of elasticity \( E_o \) | 44.18  | GPa*       |

* based on calibration, * based on core sample.

Fig. 15 (a) Fluctuation of temperature from 2014 to 2020; (b) average annual temperature fluctuation used in the numerical model.

Fig. 16 Temperature distribution inside the dam body at various months.
Based on the temperature distribution, the average characteristics and latency time were calculated at each node using Equations 3 and 4. The nodal values were then discretized to calculate the strain rate at the gauss points, and then integrated to obtain the magnitude of strain at that instant. Thereafter, the stresses at the gauss points were calculated and applied as the initial stress for the mechanical analysis.

The boundary condition of the numerical model was determined based on the geological information. The dam was constructed on a bed rock with an average modulus of elasticity of 34.5 GPa. Bui (2018) studied the effect of elastic foundation in the instantaneous deformation of the same dam. The study showed a radial displacement of 3.5 cm at the crest. When the numerical model of this study was tested with a rigid boundary, a similar result was obtained. Hence, a rigid boundary was used in this study.

### 3.3 Model calibration

The model was calibrated using the observed deflection data collected by Bui (2018). For reliability, the deflection data were tallied with the measurement by Thongthamchart and Raphitphan (2016). Both data were found to match with reasonable accuracy, as shown in Fig. 17.

The data show that the water level remains at or below 120 m (EL 234 masl) for approximately 70% of the time; hence, this water level is considered as the reference level for subsequent analysis.

In the calibration process, mainly three parameters were focused: viz. $\varepsilon(\infty)$, $\tau_c$ and $\tau_L$. After several trial and error, the value of $\varepsilon(\infty)$ was set at 0.075%, $\tau_c$ to 30 years, and $\tau_L$ was changed from 50 to 70 years because this setting could incorporate all the observed values, as shown in Fig. 18(a). For other analyses, $\tau_c$ and $\tau_L$ were set at 30 years and 60 years, respectively, as the base case. A similar method was used by Pan et al. (2013). After setting the parameters, the deflection of the dam for various water levels was calculated, as shown in Fig. 18(b), and it was found to match the observed values. The standard error of estimation for observed and predicted deflection lies between 2.6 to 6.0 mm for water level of 110 m to 140 m respectively as shown in Table 2. The correlation coefficient between the observed deflection and the calculated values is shown in Table 2.

#### Table 2

| Water level | 110 m (EL 224 m) | 120 m (EL 234 m) | 130 m (EL 244 m) | 140 m (EL 254 m) |
|-------------|-----------------|-----------------|-----------------|-----------------|
| Correlation coefficient | 0.95            | 0.91            | 0.77            | 0.89            |
| Standard error of estimate (mm) | 2.62            | 3.23            | 4.05            | 6.03            |

Fig. 17 Water level comparison between Bui (2018) and Thongthamchart and Raphitphan (2016).

Fig. 18 (a) Calibration of the model at a water level of 120 m; (b) estimation of deflection for various water levels; the full line is the calculated values while the observed values are shown by dots.

| Water level | 110 m (EL 224 m) | 120 m (EL 234 m) | 130 m (EL 244 m) | 140 m (EL 254 m) |
|-------------|-----------------|-----------------|-----------------|-----------------|
| Correlation coefficient | 0.95            | 0.91            | 0.77            | 0.89            |
| Standard error of estimate (mm) | 2.62            | 3.23            | 4.05            | 6.03            |
flection and calculated deflection for water level of 120 m or lower is greater than 0.9 indicating a good prediction for the cases that the dam experiences during most of its service life.

3.4 Sensitivity of the model
In this section, the results of sensitivity analyses carried out to investigate the effect of various factors influencing the behaviour of the dam are discussed.

(1) Effect of elasticity
Equations 7 and 8 indicate that the Young’s modulus of elasticity (E) gradually degrades over time owing to ASR cracking. A study was conducted to compare the difference between the analysis that utilizes constant E and the one that uses degrading E because the degradation is small, approximately 4 GPa in 100 years. As shown in Fig. 19(a), there is no significant difference between the two series. The two-parameter Kolmogorov–Smirnov test shows that $D = 0.071 < D_{lim} = 0.464$; hence, the two series are statistically similar (Pratt and Gibbons 2012). The radial deflection along the dam height, shown in Fig. 19(b), is also identical. This result confirms the observations by Saouma et al. (2007).

(2) Effect of varying monthly temperature
The complexity of the numerical model can be reduced using a static value of average temperature instead of varying the monthly temperature for the analysis duration. To verify whether it can be done, an analysis was carried out using an average temperature of 28.26°C. The evolution of deflection for both cases is shown in Fig. 20(a). The radial deflection along the dam height is

![Fig. 19](image-a.png)  
Fig. 19 (a) Effect of modulus of elasticity on the evolution of deflection over time, and (b) for a water level of 120 m along the dam height at the age of 100 years.

![Fig. 20](image-b.png)  
Fig. 20 (a) Evolution of deflection overtime for a water level of 120 m; (b) the deflection pattern of the dam at the age of 100 years.
shown in Fig. 20(b). A slightly higher deflection will inevitably be computed at the advanced age of the dam for the constant temperature case, because the exponential terms of Equations 3 and 4 vanish while considering the constant average temperature. This reduces the average value of $\tau_c$ and $\tau_L$, and increases the strain rate. The total effect is an increase in deflection at the later age of the dam. However, it can be observed that the trends of the two curves are similar. The two-parameter Kolmogorov–Smirnov test shows $D (= 0.143) < D_{lim} (= 0.464)$; hence, the two series are statistically similar. Therefore, in the absence of reliable data, a single temperature model can be used without losing appreciable precision.

(3) Effect of ambient temperature

Another analysis was carried out to monitor the effect of varying temperature on the deflection of the dam. This is a hypothetical analysis; however, it could be of interest to monitor the pattern of deflection when the dam is subjected to a high differential temperature. For the analysis, the base temperature was set at 20°C and the environmental temperature was set from 20 to 40°C. The maximum radial deflections observed in the dam crest at various ambient temperatures and water levels owing to the ASR strain are shown in Fig. 21(a). In all cases, the deflection gradually increases and flattens out at the age of approximately 70 years. Similarly, the evolution of the maximum deflections, including the thermal strain, is shown in Fig. 21(b). The ASR expansion is superimposed by the thermal expansion, resulting in a slightly higher deflection; the evolution curve for 20°C remains unchanged because of the same base temperature.

A detailed comparison of the maximum radial deflection at the age of 50 and 100 years for various temperature and water levels is shown in Table 3. The deflection can increase by approximately 45% for a temperature differential of 20°C when thermal strain is added, which is a significant quantity. However, the temperature differential over 20°C throughout the life of the dam is hypothetical and will not occur under normal circumstances. The actual annual temperature difference

| Water level | Deflection with ASR only (without thermal expansion) (m) | Deflection with ASR and thermal expansion (m) |
|-------------|----------------------------------------------------------|---------------------------------------------|
| 110 m (EL 224 m) | -0.037 -0.057 -0.068 -0.071 -0.072 -0.068 -0.070 -0.071 -0.071 -0.072 | -0.037 -0.064 -0.081 -0.090 -0.099 -0.068 -0.077 -0.084 -0.091 -0.099 |
| 120 m (EL 234 m) | -0.034 -0.054 -0.065 -0.068 -0.069 -0.064 -0.067 -0.068 -0.068 -0.069 | -0.034 -0.061 -0.078 -0.087 -0.095 -0.064 -0.074 -0.081 -0.088 -0.095 |
| 130 m (EL 244 m) | -0.029 -0.050 -0.060 -0.063 -0.065 -0.060 -0.063 -0.063 -0.064 -0.065 | -0.029 -0.056 -0.073 -0.083 -0.091 -0.060 -0.069 -0.076 -0.083 -0.091 |
| 140 m (EL 254 m) | -0.023 -0.043 -0.054 -0.057 -0.058 -0.054 -0.056 -0.057 -0.057 -0.058 | -0.023 -0.050 -0.067 -0.076 -0.084 -0.054 -0.063 -0.070 -0.077 -0.085 |

Fig. 21 Evolution of maximum radial deflection at the crest for various temperatures and water level of 120 m owing to (a) ASR strain (b) ASR strain combined with the thermal strain.
is 7.58°C for the target dam, which results in a 4% and 12% increase in deflection at the age of 50 and 70 years when thermal strains are accounted. However, the thermal strain recovers when the temperature drops; thus, in normal cases, it can be neglected, as discussed in the above section.

(4) Effect of strain
Another important input parameter in the numerical analysis is the magnitude of the final ASR strain ($\varepsilon_\infty$). The analysis was conducted by applying a strain from 0.00045 to 0.0015 that corresponds to 30% to 100% of 0.0015 strain value (measured during the accelerated test, Fig. 12). It must be noted that the accelerated test at 80°C in 1 mol/l NaOH solution produces low viscous ASR gels with high alkali content and may be higher than the actual filed strain. However, the strain from accelerated test is used here because it captures the worst case scenario. The temperature and other variables were set constant. The evolution of radial deflection at the crest for a hydrostatic load of 120 m and various input strains is shown in Fig. 22(a). As expected, the magnitude of deflection increases linearly with an increase in the input strain. This is true for water levels from 110 m to 140 m, as shown in Fig. 22(b). Note that the model calibrated at 50% yielded the optimum result. Interestingly, in the experiment by Kawabata et al. (2020), the ASR-DEF-affected specimens manifested approximately 50% of the expansive strain in the field compared to the specimens in the laboratory, which suggests the existence of a similar correlation for ASR affected structures. This should be verified by experimental studies.

4. Deflection variation of arch with variable parameters

The calibrated model was used to predict the future expansion and possible damage locations in the dam. Two approaches were used for the prediction. In the first approach, a deterministic method was used by setting $\tau_c$ as 30 and $\tau_L$ as 50, 60, and 70 years. These values were selected based on the model calibration as they could incorporate the observed values. The radial deflection at the dam centre line, using the deterministic approach, for a water level of 120 m is shown in Fig. 23(a), and the distribution of deflection for various ages are shown in Fig. 23(b). At the age of 100 years, the deflection lies between 54 and 66 mm.

In the probabilistic method (Monte Carlo), the input parameters, $\varepsilon_\infty$, $\tau_c$, and $\tau_L$, are set by assuming a normal distribution with the parameters shown in Table 4. However, practically, these three parameters are not known; thus, they have to be estimated based on historic data of similar structures, as shown in Fig. 14. The output of the probabilistic analysis, with input variables and radial deflection at the dam crest at the age of 100 years for a water level of 120 m is shown in Fig. 24(a). The deflection has a mean value of 61.68 mm and a standard deviation of 28.04 mm. Values for other cases are shown in Table 4. The possible deflection and standard deviation for various other water levels at the age of 70 and 100 years are shown in Fig. 24(b).

In addition to deflection, the other major parameter of interest is the crack-susceptible zone. Any area exceeding the tensile or compressive strength of the concrete has the potential for cracking. The distribution of principal stress in the dam body is shown in Fig. 25. Owing to the arch action of the dam, the increase in the ASR strain increases the compressive stress, whereas a small tensile stress of less than 1 MPa is generated without ASR expansion. Thus, there is less likelihood of tensile cracks owing to the expansion. However, in the future, if the ASR progresses beyond the predicted values, some compressive cracks may appear in the downstream face despite the maximum compressive stress at

![Fig. 22 (a) Evolution of deflection owing to various level of ASR strain for a water level of 120 m; (b) deflection of the dam for various water levels at the age of 100 years.](image-url)
the age of 100 years is at most approximately 15 MPa, which is sufficiently small to avoid cracking. Fortunately, this is an aggregable condition in terms of risk analysis because the appearance of cracks in the downstream face can be easily detected and repair can be initiated. Furthermore, the effect of reinforcement steel has not been accounted for in this study, mainly owing to the lack of data and its low percentage. A recent study has shown that steel can partially resist the expansion and provide safety against cracking when the ASR is at

| Parameters | Mean (∞) | Standard deviation (∞) |
|------------|----------|------------------------|
| ε (x)      | 0.00075  | 0.00025                |
| τ_c (year) | 30       | 10                     |
| τ_L (year) | 60       | 20                     |

| Water Level | Mean (mm) | Standard deviation (mm) |
|-------------|-----------|-------------------------|
| 110 m (EL 224 m) | 45.71      | 23.47                   |
| 120 m (EL 234 m) | 42.57      | 23.31                   |
| 130 m (EL 244 m) | 37.70      | 23.47                   |
| 140 m (EL 254 m) | 31.05      | 23.72                   |

| Water Level | Mean (mm) | Standard deviation (mm) |
|-------------|-----------|-------------------------|
| 110 m (EL 224 m) | 64.72      | 28.21                   |
| 120 m (EL 234 m) | 61.68      | 28.40                   |
| 130 m (EL 244 m) | 57.14      | 28.40                   |
| 140 m (EL 254 m) | 50.53      | 28.52                   |

Table 4 Variation of input and output parameters.

Fig. 23 (a) Prediction of deflection of the dam at the age of 70 years and 100 years using a deterministic approach for the water level of 120 m; (b) deflection of the dam for various age.

Fig. 24 (a) Probabilistic prediction of the deflection of the dam for the water level of 120 m; (b) deflection for various water levels with the standard error at the age of 100 and 70 years.
its early age, that is, when the stress level is low (Li et al. 2020). This will provide additional safety against crack formation in future.

5. Conclusion

In this study, petrographic analysis and SEM imaging of the concrete core were performed for the diagnosis of an arch dam that confirmed the occurrence of ASR in the dam. The accelerated ASR test showed that the maximum strain of approximately 0.15% indicating a potential for future expansion. Thus, to assess the behaviour of the dam in the future, a time-dependent analysis was carried out.

A coupled thermo-chemo-mechanical analysis was conducted to account for the ASR swelling using a finite element method. Using the annual temperature variation in dam body, the ASR strain and stress were calculated. Thereafter, the deflection and principal stresses in the dam were calculated. The model was calibrated to match the observed deflections. The unpredictability of the model was accounted for by providing a possible range of deflection values instead of a single value.

It is predicted that, at the age of 100 years of the dam (since 1964), the maximum deflection will lie between approximately 54-66 mm towards the upstream direction. The reliability of this prediction was further verified using Monte Carlo simulation, which estimated an upstream deflection of 61 mm with a standard deviation of 28 mm at the same age.

Similarly, the principal stress distribution in the dam shows that the dam is predominantly in a compressed condition and safe against cracking at the current rate of reaction. This study predicts the possible region where
problems may occur if the reaction is accelerated; however, note that the field data are insufficient to have firm confidence. The model described in this study should be further refined by collected deflection, stress data, and reinforcement details. By incorporating the measured values, a more accurate prediction can be made.

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