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Factors influencing hysteresis characteristics of concrete dam deformation

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Abstract

Thermal deformation of a concrete dam changes periodically, and its variation lags behind the air temperature variation. The lag, known as the hysteresis time, is generally attributed to the low velocity of heat conduction in concrete, but this explanation is not entirely sufficient. In this paper, analytical solutions of displacement hysteresis time for a cantilever beam and an arch ring are derived. The influence of different factors on the displacement hysteresis time was examined. A finite element model was used to verify the reliability of the theoretical analytical solutions. The following conclusions are reached: (1) the hysteresis time of the mean temperature is longer than that of the linearly distributed temperature difference; (2) the dam type has a large impact on the displacement hysteresis time, and the hysteresis time of the horizontal displacement of an arch dam is longer than that of a gravity dam; (3) the reservoir water temperature variation lags behind of the air temperature variation, which intensifies the differences in the horizontal displacement hysteresis time between the gravity dam and the arch dam; (4) with a decrease in elevation, the horizontal displacement hysteresis time of a gravity dam tends to increase, whereas the horizontal displacement hysteresis time of an arch dam is likely to increase initially, and then decrease; and (5) along the width of the dam, the horizontal displacement hysteresis time of a gravity dam decreases as a whole, while the horizontal displacement hysteresis time of an arch dam is shorter near the center and longer near dam surfaces.

Keywords: Concrete dam; Displacement; Hysteresis; Temperature; Analytical solution

1. Introduction

The measurement and interpretation of dam deformation data is an important part of dam safety evaluation and has been studied by various researchers (Li, 1992; Wu et al., 2007a, 2007b; Zhang et al., 2008; Jesung et al., 2009; Gu et al., 2011). For a concrete dam, the total deformation is generally divided into various components, including a hydrostatic component, a thermal component, and a time-dependent component (or irreversible component) (Bonaldi et al., 1977; Fanelli and Giuseppetti, 1982; Wu, 2003; Gu and Wu, 2006; Xu et al., 2014). The thermal component, which is the topic of this paper, is the deformation caused by the change of the outside temperature.

In the last decade, a few studies have explored the hysteresis characteristics of concrete dam deformation. Xu et al. (2012) pointed out that the variation of the thermal displacement component lags behind the variation of the air temperature, and this lag is known as the hysteresis time. According to previous interpretations, the reason for the hysteresis time is the low heat conduction velocity in concrete (Troxell and Davis, 1956; Neville, 1963; Li et al., 1996). However, in practice we find that the hysteresis time of the horizontal displacement of different dams may differ significantly even if the dam width and thermal conductivities are similar. The displacement hysteresis time of a narrow arch dam is often longer than that of a wide gravity dam. The low heat conduction velocity in concrete alone cannot fully explain

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this phenomenon. Zhang et al. (2015) derived analytical solutions of the hysteresis time of thermal deformation for a cantilever beam and an arch ring and pointed out that the dam type has a large impact on the hysteresis time of dam thermal deformation. However, their study was only based on theoretical analysis and few factors were considered. Therefore, it is necessary to study the factors influencing the displacement hysteresis time from additional perspectives.

This study mainly focused on the effects of dam type, reservoir water temperature, and spatial position on the displacement hysteresis time as determined with the analytical method and numerical simulation. Some case studies have also been examined to further verify the validity of conclusions.

2. Quasi-stable mean temperature and equivalent linearly distributed temperature difference in concrete dam

Since the heat conduction in a concrete dam is mainly determined by the temperature at the upstream and downstream surfaces of the dam, which can be approximated by one-dimensional heat conduction along the thickness of an infinite slab, this principle can be applied in the following analysis. Assuming that the thickness of the infinite slab is l, and the surface temperature changes according to the cosine function with different amplitudes and phases, the heat conduction equation can be expressed as

$$\frac{\partial T}{\partial \tau} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{1}$$

The boundary conditions are as follows:

$$T = \begin{cases} A_2 \cos[\omega(\tau - \varepsilon)] & x = 0 \\ A_1 \cos(\omega\tau) & x = l \end{cases}$$

where T is the temperature, α is the thermal diffusivity, τ is time, A_1 is the amplitude of the boundary temperature at $x = l$, A_2 is the amplitude of the boundary temperature at $x = 0$, ω is the circular frequency of temperature change, and ε is the hysteresis time of the boundary temperature at $x = 0$ relative to the boundary temperature at $x = l$.

In thermal deformation and stress analysis, temperature is typically divided into three parts: the mean temperature T_{m}, linearly distributed temperature difference T_{d}, and nonlinearly distributed temperature difference T_{n}. For a free slab whose deformation is unconstrained, T_{m} and T_{d} will produce tensile deformation and rotation, respectively, while T_{n} will only cause thermal stress and have no effect on the deformation. Therefore, only T_{m} and T_{d} need to be considered in the hysteresis analysis for concrete dams. They can be computed as follows (Zhu, 1999):

$$T_{\mathrm{m}} = \frac{1}{2} k_{\mathrm{m}} \{A_1 \cos[\omega(\tau - \theta_{\mathrm{m}})] + A_2 \cos[\omega(\tau - \theta_{\mathrm{m}} - \varepsilon)]\} \tag{2}$$

$$T_{\mathrm{d}} = \frac{1}{2} k_{\mathrm{d}} \{A_1 \cos[\omega(\tau - \theta_{\mathrm{d}})] + A_2 \cos[\omega(\tau - \theta_{\mathrm{d}} - \varepsilon)]\} \tag{3}$$

where

$$k_{\mathrm{m}} = \frac{1}{\zeta_0} \sqrt{\frac{2(\mathrm{ch}\zeta_0 - \cos\zeta_0)}{\mathrm{ch}\zeta_0 + \cos\zeta_0}} \tag{4}$$

$$k_{\mathrm{d}} = \sqrt{a_1^2 + b_1^2} \tag{5}$$

$$\zeta_0 = l\sqrt{\frac{\omega}{2\alpha}} \tag{6}$$

$$a_1 = \frac{6\sin(\omega\theta_{\mathrm{m}})}{\zeta_0^2 k_{\mathrm{m}}} \tag{7}$$

$$b_1 = \frac{6}{\zeta_0^2}\left[\frac{1}{k_{\mathrm{m}}}\cos(\omega\theta_{\mathrm{m}}) - 1\right] \tag{8}$$

$$\theta_{\mathrm{m}} = \frac{1}{\omega}\left[\frac{\pi}{4} - \tan^{-1}\left(\frac{\sin\zeta_0}{\mathrm{sh}\zeta_0}\right)\right] \tag{9}$$

$$\theta_{\mathrm{d}} = \frac{1}{\omega}\tan^{-1}\left(\frac{b_1}{a_1}\right) = \frac{1}{\omega}\tan^{-1}\left[\frac{\cos(\omega\theta_{\mathrm{m}}) - k_{\mathrm{m}}}{\sin(\omega\theta_{\mathrm{m}})}\right] \tag{10}$$

According to Eqs. (2) and (3), θ_{m} and θ_{d} represent the hysteresis times of the mean temperature T_{m} and linearly distributed temperature difference T_{d}, respectively. For the sake of simplicity, we first assume that ε in Eqs. (2) and (3) is 0 (the effect of ε will be analyzed in section 4.2), and then calculate the relationship between the hysteresis times θ_{m} and θ_{d} and the slab thickness l for different thermal diffusivities α, as shown in Fig. 1, where the thermal diffusivity ranges from 0.05 to 0.15 m^2/d, covering the common range of concrete thermal diffusivity. The circular frequency is $\omega = 2\pi/365$. That is, the cycle of external ambient temperature is 365 days. The following can be seen in Fig. 1:

(1) $\theta_{\mathrm{m}} > \theta_{\mathrm{d}}$ when the slab thickness is the same, indicating that the hysteresis time of the horizontal displacement of an arch dam is longer than that of a gravity dam, which will be discussed in detail below.

(2) The hysteresis time θ_{m} of the mean temperature increases rapidly with the slab thickness, and then decreases slightly, and remains nearly unchanged at a value of $0.25\pi/\omega$ when the slab thickness is greater than 15 m.

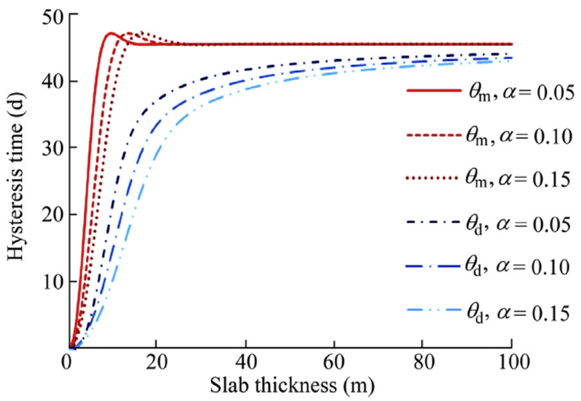

Fig. 1. Relationship between slab thickness and hysteresis times of average temperature and linearly distributed temperature difference.