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Observed displacement data-based identification method of structural damage in concrete dam

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ABSTRACT

A method for localization and severity assessment of structural damages in concrete dams is proposed. The algorithm works are based on observed displacement data that respond from the structures. Statistical pattern recognition based structural damage detection is often developed exploiting the methods of inversion analysis. The relationship between the observed displacement and damage identification of concrete dams is studied. By using the inversion method, the functional relationship between the observed displacement and damage information is developed to calculate the damage defining parameters, which are damage location and severity, are updated through an optimization scheme. Meanwhile, the damage index of a concrete dam is determined with these methods and principles. These indexes have been applied into the safety monitoring of that dam and satisfactory result has been achieved.

1. Introduction

At present, approximately 150,000 concrete dams can be found in the world. There are 600 concrete dams with a height of more than 100 m, which have played huge economic benefits in flood control, power generation, and irrigation [1]. With the long service time and the combined effects of environmental load, fatigue effect, corrosion, and aging of materials, these structures exhibit damage accumulation [2]. Therefore, researching the localization and severity assessment of structural damages can considerably reduce the maintenance cost, ensuring the safe operation of a project. The methods of structural damage detection include the visual method and the local damage detection method, which use specific instruments and equipment, with the former requiring a general understanding of easily accessible damage positions, a long and costly testing cycle, and limited practical application. The structural damage detection method that is based on dynamic characteristics analyzes the vibration characteristics that reflect the change in the structural physical parameters [3]. Salawu summarized damage detection that uses the change of frequency [4], while the Chao utilized the singular spectrum analysis for structural damage localization [5]. The damage detection method based on dynamic characteristics is applied in reinforced concrete beams and other structures with small volume and sensitive dynamic characteristics [6]. However, for large civil engineering structures, such as high arch dams and gravity dams that often have low frequency characteristics, frequency variation is not obvious and the detection method based on the dynamic characteristics is not suitable. Another method of structural damage detection is based on the static monitoring data obtained by embedding monitoring instruments in large hydraulic structures, which has been rapidly developed in recent years, creating an early warning model of concrete dams [7]. By contrast, the structural damage identification method of concrete dams is still in

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development. Therefore, the damage identification method based on the static measured data has broad application prospects in the field of dams.

2. Identification method of structural damage based on observed displacement data of concrete dam

After several years of operation, the actual material parameter value and the design material parameter value of the concrete dams are different because of the structural damage. These factors have a great influence on the deformation of the dam in that the actual monitoring deformation data and the design deformation data deriving from the numerical simulation are not the same. Therefore, it is necessary to use the inversion method of observed displacement data to obtain the actual material parameters of the dams. The material parameters of the dams include: the elastic modulus, the shear modulus, and the bulk density. The elastic modulus is the most important parameter of engineering materials, which can reflect the mechanical properties of materials. Therefore, this paper studies the structural damage identification method based on the theory of elastic modulus inversion method.

2.1. Conventional inversion analysis method for elastic modulus of concrete dam

The loads of hydraulic structures include water pressure, sediment pressure, temperature, and earthquake effect. Under normal operating conditions, the hydraulic structure deformation is mainly affected by water pressure, temperature and aging effect [8]. When the dam is subjected to extreme loads such as earthquake or flood, the equation of the time effect components need to be changed, and the displacement of the earthquake should to be added. In this paper, the structural damage analysis is under normal operating conditions. The displacement δ can be divided into three parts, namely water pressure component δ_H, thermal components δ_T, and time effect components δ_θ [9]. Therefore, the displacement δ is written as

$$\delta = \delta_H + \delta_T + \delta_\theta \quad (1)$$

where H is water depth; T is fluctuating temperature; and θ is the period from initial time.

Assuming that the dam body and foundation are in the elastic stage under the function of water pressure, the average elastic modulus of the dam concrete and the foundation rock are E_c and E_r, respectively. The equilibrium equation of the entire structure is

$$[K]\{\delta_H\} = \{R_H\}. \quad (2)$$

Within the linear elastic range, $[K]$ and E have a linear relationship. It can be derived from Eq. (2) that

$$\{\delta_H\} = \left[\overline{K}\right]^{-1}\{R_H\} \quad (3)$$

$$\{\delta_H\} = \left\{\overline{\delta_H}\right\}/E. \quad (4)$$

For a dam under a certain water pressure, $\{\overline{\delta_H}\}$ is a fixed number that relates to the structure property and water pressure. Therefore, Eq. (4) indicates that the water pressure displacement δ_H and the elastic modulus of the dam concrete E have an inverse proportion relation.

2.2. Improved inversion analysis method for elastic modulus of concrete dam

The water pressure displacement δ_H and the elastic modulus E of dam concrete have an inverse proportion relation theoretically. Eq. (4) is built on the assumption of the elastic condition. However, because of the nonlinear elastic condition of the material, structure size, and construction factors in the actual operation, the function $\delta_H = f(\frac{1}{E})$ of the dam and the foundation tend to be inverse proportion relation approximately. Fig. 1 shows the actual functional relation curve $\delta_H = f(\frac{1}{E})$ between the elastic modulus E and the water pressure component δ_H. This paper proposes a method based on the differential element method to transform the nonlinear problem into a linear problem.

The core idea of the differential element method is that a curve tends to be a straight line when $\Delta x \rightarrow 0$, $f'(E_0) = \lim_{\Delta x \rightarrow 0} \frac{\Delta y}{\Delta x}$. The value of $f'(E_0)$ is a fixed constant. The smaller Δx is, the closer $\frac{\Delta y}{\Delta x}$ is to the constant. By analogy to the differential element method, when two adjacent observed water pressure displacement, namely δ_{Ht_1}, δ_{Ht2}, at an adjacent measuring time satisfy the equation of $\Delta t = t_2 - t_1 \rightarrow 0$, where $\Delta\delta_H$ is the variable quantity of displacement and the water load, ΔH is the variable quantity of the water load, ΔE is the variable quantity of the elastic modulus.

ΔE is caused by the action of the loads. With the structural resistance, the ΔE has a lag effect. Thus, in a short period of time Δt, the variable quantity of elastic modulus $\Delta E = 0$, the variable quantity of the water load $\Delta\delta_H$ is caused by the variable quantity of water load ΔH. Therefore, based on Eq. (4), the equation is derived as the following.

$$\delta_H = f(H)/E \quad (5)$$