Cold Regions Science and Technology 151 (2018) 267–287

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Indirect monitoring of distributed ice loads on a steel gate in a cold region

Meng Zhang[a], Xianqiang Qu[a,b,*], Hamed Kalhori[b], Lin Ye[b]

[a] Engineering Structure Lab, College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China
[b] Laboratory of Smart Materials and Structures (LSMS), School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, NSW 2006, Australia

ARTICLE INFO

Keywords:
Steel gate
Ice load
Load identification
Inverse method

ABSTRACT

A steel gate is one of the major components of a hydraulic power station for storing water and monitoring the water level. In cold regions, the temperature decreases to well below the freezing point, and the water turns to ice, which can apply high loads on the steel gate, leading to large deformations and failure of the gate. This study aims to monitor and analyse the ice load distribution on a steel gate using an inverse method. As a case study, a steel gate at the hydraulic station on the Songhua River in Harbin is selected. The steel gate is equipped with several vibrating wire strain gauges, and deformation data for various locations on the structure was collected for 100 days. As experimental identification of the system transfer matrix requires information concerning the actual loads, which is not directly attainable, the transfer matrix was constructed using a finite element method. Five inverse methods were verified with a certain number of load patterns to determine the optimal method. The ice load distribution obtained using the optimal method is verified with the deformation data, indicating accurate load identification. Consequently, variation in the ice load distribution during the freezing period is monitored, and the relationship between the total ice force and temperature is obtained. During the winter of 2015–2016, the average ice line load gradually increased until reaching a maximum of approximately 25 kN/m on 11 Dec. 2015. Subsequently, the ice line load fluctuated between 17 and 25 kN/m. Finally, the ice released all of the force within 3 days beginning on 15 Mar. 2016.

1. Introduction

Steel gates are control structures that regulate the water level in hydraulic structures. In cold regions, a large area of ice is in contact with the steel gate, and a high ice load may be applied to the gate, leading to deformation of the gate. If plastic deformation occurs, the steel gates may become so deformed that it is difficult to lift them up, which affects the safety and maintenance of the hydraulic structure. Unfortunately, ice loads are not included in the existing design code for steel gates in water resources and hydropower projects in China (2013). During the freezing period, only measures such as breaking the ice in front of the gates, stirring with submerged pumps to resist freezing, or heating of the gates are recommended. The measurements to be obtained under different environmental conditions depend on the experience of the operators and the field conditions, but the cost of these measurements is undesirably high. Therefore, monitoring and analysing the distribution of ice loads on steel gates in cold regions is necessary to ensure the maintenance and safety of hydraulic structures.

Fluctuations in the ice load can be influenced by many factors, including temperature, thickness of the ice layer, and the water level, which were studied extensively by Taras et al. (2011). Comfort and Abdelnour (1992) suggested that, near a dam, the water drop can produce a tensile stress in the upper part of the ice layer and a compressive stress in the lower part, while the rise of the water level can lead to tension in the lower part and compression in the upper part. Stander (2006) quantitatively studied the stress of an ice layer produced by a change in the water level.

Comfort et al. (2004) asserted that ice load on a dam is primarily caused by thermal expansion of the ice layer and water level fluctuation. The thermal expansion load depends on the ice temperature at the beginning of an event, the temperature gradient of the ice layer, and the rate of temperature change. In addition, Comfort et al. (2004) pointed out that snow on the ice acts as an isolation layer between the cold air and the ice layer, which affects the temperature gradients and temperature change, and produces a higher load on the dam.

Greater ice thickness can produce higher loads on a dam, which indicates that ice thickness is an important factor for the ice load (Comfort et al., 2003). In the code for the design of hydraulic structures against ice and freezing action in China (2006), the design load of the static ice extrusion force of a dam depends only on the ice thickness.

Many complex factors affect the ice load of a dam or gate in cold regions. Therefore, it is difficult to accurately determine the ice load on

* Corresponding author at: Engineering Structure Lab, College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China.
E-mail address: quxianqiang@hrbeu.edu.cn (X. Qu).

https://doi.org/10.1016/j.coldregions.2018.04.001
Received 22 November 2016; Received in revised form 22 March 2018; Accepted 4 April 2018
Available online 07 April 2018
0165-232X/

a steel gate with theoretical analysis, numerical simulation, or empirical formula, and it is especially difficult to obtain the distribution of ice loads. However, ice load monitoring is an effective method.

Ice load monitoring has been widely studied in ocean engineering, particularly for the identification of dynamic ice loads on the piles or bases of ocean structures (Yue and Bi, 1998, 2000; Barker et al., 2005; Gravesen et al., 2005). Monitoring of the distribution of ice loads on hydraulic structures has been performed mostly for dams, bridge piers, or lighthouses. Bjerkås (2007) presented a review of experimental methods for the identification of full-scale ice loads on fixed structures that fell into four classifications: interfacial methods, structural response monitoring, Newton's second law, and hindcast calculations.

Gong et al. (1999) monitored static ice loads on wooden and steel stoplogs at the Seven Sisters Generating Station with stress meters and strain gauges from the winter of 1995–1996 to the winter of 1997–1998. Results of the linear ice loads were reported, and the maximum ice line load of the steel stoplogs was approximately 57 kN/m. Long-time monitoring of the pressure from the ice at eight positions was analysed by Comfort et al. (2004). The distribution of the ice load along the dam was proposed, and a maximum ice load of approximately 374 kN/m was reported. Three types of sensors were used for monitoring the ice load of dams by Taras et al. (2011), and peak load values greater than 100 kN/m were recorded at the Arnprior and Barrett Chute dams. Additionally, the ice pressure distribution at the dam wall did not vary linearly with depth. The maximum ice pressure was approximately 700 kPa near the upper surface of the ice layer. Monitoring results in the reservoir ice field also had similar characteristics.

Most of this prior research used specific sensors to monitor the stress inside the ice or at the interface between the ice and the structure, and fitting or interpolation methods were used to obtain the linear force of the ice load.

Although these studies provide useful references for the design of hydraulic structures, the distribution of the ice load on a steel gate is still unclear, particularly the distribution along the width and height of the gate. Structural health monitoring (SHM) and the load identification method can be used to determine the ice load distribution when the structure response is monitored.

Brown (2007) proposed an indirect method to monitor the structure response of the Confederation Bridge. The data from tilt meters were used to calculate the static force, and a frequency analysis was performed to identify the load event (Brown et al., 2010).

Load identification is a key topic in structural health monitoring, and most of the research in this area is focused on dynamic load identification (Inoue et al., 2001; Kalhori et al., 2016). Continuous distribution load identification was initially proposed for aeroplane structures to evaluate the surface pressure and aerodynamic loads of aeroplanes. Nakamura et al. (2012) proposed a method for monitoring a continuous distribution load on the wings of an aeroplane. Strain data were used to analyse the aerodynamic loads on the wing with an inverse technique. A pseudo inverse matrix and aerodynamics equations were combined in the inverse analysis. Coates and Thamburaj (2008) used strain data to identify the flight load with an inverse interpolation technique. An optimization method for minimizing the error between the measured strain and simulated strain was used to realize the approximation. Cao et al. (1998) and Carn (2006) obtained the aerodynamic loading from strain data using neural networks. However, large amounts of priori data are needed for this method.

In this study, an average strain monitoring method was proposed to monitor the deformation of a steel gate in a hydraulic structure. The finite element method (FEM) was used to obtain the transfer matrix for the system. Then, the distribution of the ice load was inversely calculated with the Moore-Penrose pseudo inverse method (M-P). Field measurements of the steel gate deformation was conducted throughout the winter of 2015–2016, during which 24 sets of deformation and temperature data were collected each day. Finally, the ice load distribution and total ice force were estimated with the inverse technique based on the measured deformation data.

2. Theory

The identification of distributed loads is an inverse problem in structural mechanics. Such inverse problems are often ill-posed, i.e., an arbitrarily small perturbation of the data can cause an arbitrarily large perturbation of the solution. If the condition number of the transfer matrix is large, the solution of an inverse problem needs a regularization method. Regularization methods such as truncated singular value decomposition (TSVD) and the Tikhonov regularization method (TRM) (Kalhori et al., 2016; Wang et al., 2015; Hansen, 1994) provide efficient solutions for ill-posed problems.

Because the pressure of the ice on the steel gate varies slowly, the process of forming and changing the ice load can be considered a static problem. The area on the steel gate in contact with the ice is divided into a certain number of individual cells. The pressure at each individual cell is assumed to be uniform and the whole system comprising the load and deformation of the steel gate is considered to be linear. Then, the relationship between the measurement and the pressure can be expressed as:

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{Bmatrix} = \begin{bmatrix} K_{11} & K_{12} & \cdots & K_{1m} \\ K_{21} & K_{22} & \cdots & K_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ K_{n1} & K_{n2} & \cdots & K_{nm} \end{bmatrix} \cdot \begin{Bmatrix} f_1 \\ f_2 \\ \vdots \\ f_m \end{Bmatrix} \tag{1}$$

Eq. (1) is in the form $\{\varepsilon\} = [K] \cdot \{f\}$, where ε_i is the strain at location i, and a positive strain indicates expansion, n is the number of strain gauges, f_i is the uniform pressure of individual cell i, m is the total number of cells, and K is the transfer matrix; the elements in the matrix represent the reflection relationship between the uniform pressure at different individual cells and the strain measured with the gauges. For example, K_{ij} indicates the strain at location i due to the uniform pressure of individual cell j.

For a given transfer matrix $[K]$ and measurement $\{\varepsilon\}$, the applied force $\{f\}$ for a well-posed problem can be calculated as follows:

$$\{f\} = [K]^{-1} \cdot \{\varepsilon\} \tag{2}$$

where $m = n$. If $m \neq n$ and the difference between n and m is small, then $\{f\}$ can be calculated by

$$\{f\} = [K]^{+} \cdot \{\varepsilon\} \tag{3}$$

For ill-posed problems, where an arbitrarily small perturbation of $\{\varepsilon\}$ can produce an arbitrarily large perturbation of $\{f\}$, several numerical tools, including truncated singular value decomposition and the Tikhonov regularization, can be used to obtain a meaningful solution for $\{f\}$.

2.1. Transfer matrix calculation

The transfer matrix of the system is established by applying a unit uniform pressure to a single individual cell and recording the corresponding response at the measurement points. This process is then repeated for each individual cell.

Assume $\{f\} = \begin{Bmatrix} f_1 \\ 0 \\ \vdots \\ 0 \end{Bmatrix} = \begin{Bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{Bmatrix}$. Then,

$$\begin{Bmatrix} K_{11} \\ K_{21} \\ \vdots \\ K_{n1} \end{Bmatrix} = \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_3 \end{Bmatrix} \tag{4}$$