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Distributed optical fiber-based theoretical and empirical methods monitoring hydraulic engineering subjected to seepage velocity

Huaizhi Su [a,b,*], Shiguang Tian [b], Shusheng Cui [c], Meng Yang [b], Zhiping Wen [d], Wei Xie [b]

[a] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, China
[b] College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, China
[c] National Engineering Research Center of Water Resources Efficient Utilization and Engineering Safety, Nanjing, China
[d] Dept. of Computer Engineering, Nanjing Institute of Technology, Nanjing, China

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ABSTRACT

In order to systematically investigate the general principle and method of monitoring seepage velocity in the hydraulic engineering, the theoretical analysis and physical experiment were implemented based on distributed fiber-optic temperature sensing (DTS) technology. During the coupling influence analyses between seepage field and temperature field in the embankment dam or dike engineering, a simplified model was constructed to describe the coupling relationship of two fields. Different arrangement schemes of optical fiber and measuring approaches of temperature were applied on the model. The inversion analysis idea was further used. The theoretical method of monitoring seepage velocity in the hydraulic engineering was finally proposed. A new concept, namely the effective thermal conductivity, was proposed referring to the thermal conductivity coefficient in the transient hot-wire method. The influence of heat conduction and seepage could be well reflected by this new concept, which was proved to be a potential approach to develop an empirical method monitoring seepage velocity in the hydraulic engineering.

1. Introduction

In recent years, large numbers of dams and dikes have been built in many countries ([2,1,3,14]. However, seepage-induced dams or dikes failure is a frequently encountered hazard, which covers internal erosion, slope instability, dam burst, and so on [9,16,18]. The insufficient seepage control measures and absence in discovering hidden dangers timely have led to above failures. The obvious characteristics of the embankment dam seepage include space–time randomness, concealment, initial slight level, etc. Moreover, the conventional point monitoring instrument have been on more typical sections and large grid spacing layout, which could lead to large monitoring blind areas, discontinuity monitoring spatial and even missed detections [11,17,10,12]. With the recent rapid development of fiber optic sensing technologies, the potential of distributed optical fiber temperature sensor system for dams and dikes seepage monitoring has been recognized [8,5,15,4,7]. However, the technology still stays in its infancy barely for some qualitative identification [13,6]. This paper mainly depends on the theoretical analysis and the model test, on the basis of reasonable design of the test platform and test process. The principle and method of the seepage monitoring implementation based on DTS are studied to monitor and identify saturation line and seepage velocity in embankment dams.

In this paper, the general principle is presented to monitor the dam seepage velocity based on DTS through the analysis on the coupling problems between seepage field and temperature field of embankment dams. A DTS-based experiment monitoring seepage velocity is designed. The inversion analysis method is introduced to identify seepage velocity in the hydraulic engineering by considering the coupling influence among the seepage and temperature field. The theoretical model of monitoring seepage velocity is constructed for embankment dam, dike and other hydraulic structures. The model test is implemented to analyze the relationship between seepage velocity and the effective thermal conductivity, and a DTS-based empirical method monitoring seepage velocity in the hydraulic engineering is presented.

2. Basic principle of identifying seepage behavior based on fiber-optic temperature sensor

The seepage could cause local irregular temperature field of hydraulic structures, which can be located and detected if the abnormal temperature is timely monitored. The coupling influence

* Corresponding author at: State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China.
E-mail address: su_huaizhi@hhu.edu.cn (H. Su).

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Notation

The following symbols are used in this paper

C	parameter determined by the geometrical form and arrangement of particles
d	particle diameter
γ	water bulk density
μ	dynamic viscosity coefficient of water
J	seepage gradient
k	permeability coefficient
k_x, k_y and k_z	permeability coefficient along the x, y and z direction
V_{T_x}	water circulation caused by temperature variation
D_T	water diffusivity under temperature action
$\frac{\partial T}{\partial x}$	temperature gradient along the one-dimensional coordinate direction
V_{T_y} and V_{T_z}	seepage velocity along the y and z direction
∇	Hamiltonian operator
S_S	water storage coefficient
q_x	heat flow along with one-dimensional axis of x direction
c_w	specific heat of wate
ρ_w	water density
v	seepage velocity
λ	thermal conductivity
c	specific heat of medium
ρ	medium density
Q_T	source term
$T_0(x)$	temperature distribution under temperature gradient
$T_H(x)$	temperature distribution under water gravity potential
$H_0(x)$	water level distribution driven by gravitational potential
$H_T(x)$	water head distribution driven by the temperature potential
Ω	model area
Γ_1	inside boundary of the model
Γ_0	outer boundary of the model
n	outward normal direction of the boundary surface
θ	absolute temperature rise for optical cable
T	temperature of the cable at the time τ
T_0	initial cable temperature without being heated
q	heating power per unit length
τ	heating time
a	thermal diffusion coefficient
r_0	radius of hot-line
C	specific heat capacity
R	multiple-correlation coefficient
H	seepage head of earth dam
l	model length of one dimensional stable seepage field and temperature field
x	one-dimensional x direction axis
$\lg k$	logarithmic value of permeability coefficient

is analyzed between seepage field and temperature field in embankment dam or dike engineering. Thus, a simplified model, namely seepage monitoring model, is built to describe the coupling relationship of two fields. The basic principle identifying seepage behavior according to optical fiber temperature is presented.

2.1. Coupling relationship analysis between seepage field and temperature field

2.1.1. Influence of temperature variation on seepage

Temperature variation could influence the physical and chemical parameters of porous medium and water, which will further affect the internal distribution of seepage field in dams. Among the parameters of porous medium, the porosity, specific heat, thermal conductivity and temperature conductivity are closely related to the distribution of seepage and temperature field. These parameters will change so minimal or even will not change any more when the temperature fluctuation is below 10 °C. Therefore, the temperature variation could be considered to be no influence on the parameters above. Among the water physical and chemical parameters, such as density ρ, bulk density γ, viscosity μ, thermal conductivity λ, thermal expansion coefficient θ, water temperature conductivity α, specific heat c and movement viscous coefficient v, are closely related to the coupling field. In particular, the variation of the thermal expansion coefficient and the movement viscous coefficient could directly affect the water seepage properties, which should be taken consideration into the analysis of the coupling calculation and analysis.

The permeability coefficient of the medium (such as porous medium particles) indicates the penetration strength. It has to do with porous medium type, compactness, temperature, dynamic seepage viscosity and so on. The Darcy permeability coefficient of porous medium particles can be expressed by

$$k = Cd^2 \frac{\gamma}{\mu} J \tag{1}$$

where C is the parameter determined by the geometrical form and the arrangement of particles; d is the particle diameter; Cd^2 represents the medium permeability, which only does with the porous constitution structure (particle size, character and arrangement); γ is the water bulk density; μ is the dynamic viscosity coefficient of water; J is the seepage gradient.

As shown in Eq. (1), the permeability coefficient of porous medium is a function of water temperature and it is inversely proportional to the liquid dynamic viscous coefficient.

To some extent, the distribution of seepage field is influenced by temperature field though permeability. In addition, the temperature potential gradient caused by temperature difference will also affect the water movement. Due to itself complexity of temperature potential, the influence of temperature potential to water movement is only represented by a kind of empirical expression of temperature gradient. In one dimensional case,

$$V_{T_x} = -D_T \frac{\partial T}{\partial x} \tag{2}$$

where V_{T_x} is the water circulation caused by temperature variation; D_T is the water diffusivity under temperature action, which describes the impact contained the thermal expansion coefficient of the porous medium and physical and chemical variation coefficient in water; $\frac{\partial T}{\partial x}$ is the temperature gradient along the one-dimensional coordinate direction.

Then, the seepage velocity along the x direction is

$$V_{T_x} = -k(T)\frac{\partial H}{\partial x} - D_T \frac{\partial T}{\partial x} \tag{3}$$

Similarly, the seepage velocities along the y and z directions are

$$V_{T_y} = -k(T)\frac{\partial H}{\partial y} - D_T \frac{\partial T}{\partial y} \tag{4}$$

$$V_{T_z} = -k(T)\frac{\partial H}{\partial z} - D_T \frac{\partial T}{\partial z} \tag{5}$$