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Distributed optical fiber-based monitoring approach of spatial seepage behavior in dike engineering

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ABSTRACT

The failure caused by seepage is the most common one in dike engineering. As to the characteristics of seepage in dike, such as longitudinal extension engineering, the randomness, strong concealment and small initial quantity order, by means of distributed fiber temperature sensor system (DTS), adopting an improved optical fiber layer layout scheme, the location of initial interpolation point of the saturation line is obtained. With the barycentric Lagrange interpolation collocation method (BLICM), the infiltrated surface of dike full-section is generated. Combined with linear optical fiber monitoring seepage method, BLICM is applied in an engineering case, which shows that a real-time seepage monitoring technique is presented in full-section of dike based on the combination method.

1. Introduction

The length of embankments has been about 413,000 kilometers in China, playing an important role in regulating rivers and lakes, securing property and personal safety and meeting the needs of irrigation, water supply, shipping and water conservation. However, the limitation of design scheme and construction technique in the past and the imbalance between regulation and maintenance result in increasing problems, over 85 per cents of which due to the seepage [10]. Therefore, monitoring and analyzing the condition of the seepage in dike contributes to its real-time prediction.

Temperature used as a kind of natural tractor material has a unique advantage in seepage monitoring [13], and many projects have confirmed its importance in the field of monitoring seepage in dike [11]. Advanced distributed fiber temperature sensor (DTS) technology permits long-distance monitor, high spatial resolution, remote linear measurement, etc. Because of those features, using it to monitor the seepage and saturation line in dike required some useful results [12], attracting more attention from the academic to engineering. It can be seen that the main research content of this technology has just been proving the feasibility of single-point and several-point detection and sensing technology, especially for slow flow based on optical fiber recently. Because the embankment is a typical, complex, huge and random system, the locations of seepage spots are unknown. Thus, traditional arrangement method is unreasonable in economy and technology. In this paper, a modified arrangement method is presented, adopting a new method combining layer with linear arrangement, and based on difference method BLICM. A real-time monitoring technique is put forward, which built an omnibearing seepage monitor system in dike. The system has great significance in locating seepage spots punctually and accurately.

2. Theoretical monitoring model of seepage behavior

The DTS system is used to measure the distributed temperature of the heated fiber that is buried in porous medium to monitor the seepage. The basic principle is that the seepage flow involves in the heat transfer process between the fiber and soil and exchanges heat with them, leading to the temperature difference in the leakage and non-leakage place. When the leakage does not appear in the fiber position, the temperature field around the optical fiber is stable. Otherwise, when the leakage occurs in a certain part of the fiber, the original temperature field will change. The faster the velocity of the seepage flow turns, the greater the temperature changes at the leaking point. Therefore, seepage monitoring can be

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realized indirectly by monitoring the change of temperature, namely using the temperature field to feedback the seepage field. Therefore, the seepage location will be found and the relation between the temperature variation and the seepage flow velocity can be quantified. From the above, the process of heat transfer between the porous medium and the heating of the fiber need understanding deeply. On this basis, the theoretical relationship between the temperature rise of the optical fiber and the seepage flow rate as well as other variables should be established so as to achieve quantitative monitoring of seepage in porous media.

The heating fiber is regarded as one kind of line heat source that can measure the wind velocity, which was used to study the convection heat transfer between the heated fiber and pure water flow. Firstly, a pure flow velocity model based on distributed optical fiber monitoring was deduced. Based on this, a practical model for monitoring seepage in the same medium and rock and soil combined position with distributed optical fiber was obtained. To calculate the convective heat transfer between the heated fiber and the pure water flow, the Newton cooling formula can be used as

$$Q_\upsilon = A_a h(T_s - T_f) = q \tag{1}$$

where Q_υ is the convective heat transfer between the heated fiber and the flow, A_a is the heat transfer area between the optical fiber and the flow, h is the heat transfer coefficient, T_s is the surface temperature of the heated fiber, T_f is the flow temperature, q is the heating power. A_a, q, T_s and T_f can be measured and calculated directly. Only the heat transfer coefficient can't be measured directly. So the study is transformed from convection heat transfer into heat transfer coefficient. From the previous analysis, it can be seen that the heat transfer coefficient is related to the flow velocity, the structure size of the fiber and the unit weight, specific heat capacity, Kinematic viscosity coefficient and thermal conductivity of water, so it can be expressed as follows

$$h = f(u, l, \rho_w, c_w, \upsilon, \lambda_w) \tag{2}$$

where h is the convection heat transfer coefficient, u is the flow velocity, l is the structure size of the fiber, ρ_w, c_w, υ, λ_w is separately the unit weight of water, the specific heat capacity of water, the water Kinematic viscosity coefficient and the water thermal conductivity. Since ρ_w, c_w, υ and λ_w are assumed to be constants, when the size of the fiber, l, is determined, the convective heat transfer coefficient formula is simplified as $h = f(u)$, which means the heat transfer coefficient is only the function of the flow velocity. In order to study and calculate the heat transfer coefficient h, it is necessary to know the characteristic numbers and characteristic formula of the heat transfer form of the external heat transfer tube. Because the heat transfer coefficient is calculated according to the similarity principle of the characteristic numbers and the characteristic formula.

2.1. Characteristic numbers

Reynolds number Re_m represents the relative size of flow inertia force and viscous force. It is a quantitative sign of flowing state, which is defined as

$$Re_m = \frac{ud}{\upsilon} \tag{3}$$

where Re_m is the Reynolds number of the swept single tube, υ is the coefficient of Kinematic viscosity, d is the outer diameter of the heating fiber.

Planck number Pr_m represents the relative size of the fluid momentum diffusion capacity and the heat diffusion capacity, which is determined by

$$Pr_m = \frac{\upsilon}{a} \tag{4}$$

where Pr_m is the Planck number of the outer swept single tube, υ is the coefficient of Kinematic viscosity, a is the temperature coefficient.

Nusselt number Nu_m represents the temperature gradient magnitude of the fluid near the heat transfer surface, which is defined as

$$Nu_m = \frac{hd}{\lambda_w} \tag{5}$$

where Nu_m is the Nusselt number of the outer swept single tube, d is the outer diameter of the heating fiber, λ_w is the water thermal conductivity.

2.2. Characteristic correlation

The characteristic formula between the characteristic numbers of the outer swept single tube is

$$Nu_m = C\,Re_m^n Pr_m^{1/3} \tag{6}$$

where C and n are constants of the outer swept single tube, When the pure water flows through the line heat source, C and n is chosen according to different Re_m Table 1). It is obviously incorrect for the seepage in porous media to use the parameters listed in the following table. As to the seepage in porous media, the parameters C and n are analyzed and determined by experiments.

2.3. Calculation of heat transfer coefficient h

Substituting characteristic numbers into the characteristic Eq. (6), the resulting expression is

$$\frac{hd}{\lambda_w} = C\left(\frac{ud}{\upsilon}\right)^n \left(\frac{\upsilon}{a}\right)^{1/3} \tag{7}$$

After the collation, the equation is

$$h = C\lambda_w d^{n-1} \upsilon^{\frac{1}{3}-n} a^{1/3} u^n \tag{8}$$

where $C\lambda_w d^{n-1} \upsilon^{\frac{1}{3}-n} a^{1/3} = D$ is a constant. The equation turns to be

$$h = Du^n \tag{9}$$

When the water flow is not perpendicular to the outer swept heated fiber (line heat source), that is, an angle φ ($0^\circ < \varphi < 90^\circ$) between the fiber and the axial direction being formed, the heat transfer coefficient is smaller than that in the vertical condition. Hence, it is necessary to multiply an impact angle correction factor in calculation. That is

$$h = c_\varphi A u^n \tag{10}$$

Combined Eqs. (1) and (9), the equation is

$$q = A_a D u^n (T_s - T_f) = A_a D u^n \Delta T \tag{11}$$

$k = \frac{\Delta T}{q}$, Eq. (11) is transformed into

Table 1
Values of C and n.

Re_m	C	n
0.4–4	0.989	0.330
4–40	0.911	0.335
40–4000	0.683	0.466
4000–4000	0.193	0.618
4000–40,000	0.0266	0.805