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Design of simulator for seepage detection in an embankment based on distributed optic fibre sensing technology*

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Abstract: Based on the temperature change in an embankment, a seepage flow simulator and monitoring system based on distributed optical fiber sensing are proposed. A simulator is designed that consists of scale model of embankment with definite length, seepage flow control cell and monitoring cell. Conventional hygrothermograph and flowmeter are employed in system dispersedly. The results from those conventional instruments will be used to compare with the data from a distributed fibre sensing DiTeSt analyzer. The simulator equipment can monitor various embankments with different boundary conditions, such as temperature, distributions of soakage line and scales. The process of producing seepage pathway and configuration of sensing cable are presented, as well as test results with a field-installed fiber optic sensing cable. The simulator and results are helpful to build reasonable configurations for field real-time monitoring of abnormal seepage flow, which also offer an effective approach to study problems related to a secured embankment.

Keywords: embankment; seepage; simulator rig; distributed optical fiber sensing; temperature monitoring

基于分布式光纤传感技术的堤坝渗流模拟系统设计

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摘　要:分析了堤坝渗流通过温度监测的可行性,提出了基于分布式光纤温度传感的堤坝渗流监测方法,设计了模拟装置;模拟监测系统由堤坝实体模型、渗流控制单元和光纤监测单元组成,采用传统的温湿度计和渗流量计对堤坝模型渗流实施单点监测,并与DiTeSt分析仪的结果比较。堤坝渗流模拟装置可实现不同水温、不同浸润线、不同规格堤坝和堤坝渗流程度的重复模拟,给出了一种野外专用的传感光缆实验结果。研究中的试验结果有利于设计合理的光缆布设和探测方案,同时为堤坝安全监测的量化研究提供有效的手段和平台。

关键词:堤坝; 渗流;模拟装置; 分布式光纤传感; 温度监测
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1 Introduction

Internal erosions such as seepage and piping are major reasons for the failure of river or reservoir embankment. A system for seepage and piping monitoring is therefore an important part of embankment surveillance. Different methods to detect defects in an embankment have been presented.

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The used techniques are: high density resistivity, electricity and electromagnetic methods where sensors are punctual. This makes it difficult to monitor large areas[1-2]. Additionally, some of these methods are complicated; some are not sensitive enough to capture small changes in the seepage flow[3-4]. With the advancement towards higher-resolution, the distributed optical fiber sensing technology has radically improved the ability to achieve accurate results and locates the position of events at 0.5 meter along the embankment[5-6]. It thus offers an interesting alternative for customers. Furthermore, since Brillouin scattering properties only depends on the fiber material, this sensing technique is absolutely stable in time. The distributed fiber technology for temperature sensing is currently applied in leakage of pipeline, in power plants or power transfer stations and concrete dams[7-8]. Those methods can not be simply introduced into a long sand embankment monitoring. If the sensing fiber is installed in a real embankment directly before studying it thoroughly, It may bring some problems: (1) It is difficult to select an embankment segment with a new non-destructive seepage pathway. (2) It will be expensive due to one-off installation of sensing fiber time after time for a different location with another seepage flow. (3) It is difficult to change the boundary conditions of a seepage. So it is necessary to design a seepage simulator, which will be a platform to optimize configurations of fiber optic sensing cables and find the relation between the seepage rate and the signal from the sensor, as well as for seeking a reasonable alarm threshold value.

2 Function and principle of the system

The designed simulator and monitoring system should have these functions:

(1) Monitoring the pressure and flux of a simulated seepage flow;

(2) Identifying classical signals under different seepages for setting alarm threshold;

(3) Creating a seepage flow whose size and boundary conditions can be controlled.

According to its functions, the simulator consists of a scale model of embankment with a definite length, a seepage flow control cell and a monitoring cell. In the monitoring cell, the Omnisens DiTeSt-STA202 analyzer is employed to acquire and analyse the data from the fiber sensing cable. fig. 1 shows the flowchart of the tested data in the system.

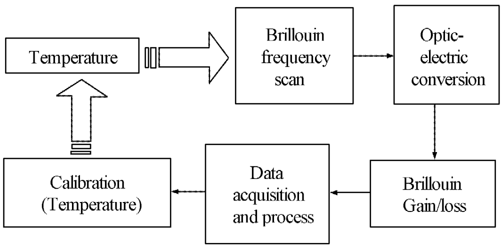


Fig. 1 Tested data flowchart

2.1 Measurement principle of distributed fiber sensing based on stimulated Brillouin scattering

The Omnisens DiTeSt-STA202 is based on an interaction of the laser light with the optical fiber material, and is the so-called Stimulated Brillouin Scattering (SBS). SBS is an intrinsic physical characteristic of the fiber material, which can deliver crucial information when used for sensing, especially about strain and temperature. Both regular single-mode communication optical fiber and cable can be used as sensing parts. fig. 2 shows the transmission of light is in tested optical fiber.

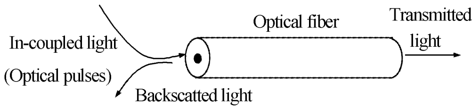


Fig. 2 Transmission of light in tested optical fiber

Backscattered light will be received and extracted from the fiber, which contains the coded information on the change of local temperature in the embankment. By scanning frequency in certain range the maximum of Brillouin frequency shift will be obtained. It is given by the following formula [6]:

$$v_B = 2nV_A/\lambda_0 \tag{1}$$

where v_B is the Brillouin frequency shift, n is the refractive index of the optical fiber core, V_A is the sound velocity, λ_0 is the wavelength of pump light. There is a linear relation between Brillouin frequency shift and the change of temperature and local strain:

$$\Delta v_B = C_{VT}\Delta T + C_{V\varepsilon}\Delta\varepsilon \tag{2}$$

where Δv_B is the change of Brillouin frequency shift, ΔT is the change of temperature, $\Delta\varepsilon$ is the change of strain, C_{VT} is the temperature coefficient of Brillouin frequency shift, $C_{V\xi}$ is the strain coefficient of Brillouin frequency shift. The temperature and strain can be calculated from the Brillouin frequency shift; the distance from detect point to light source is related to the propagation time. Then abnormal locations can then be detected after determining the distance. If the sensing cables are designed to be strain-insensitive, it is not necessary to compensate strain in these cases. Eq. (2) can be simplified:

$$\Delta v_B = C_{VT}\Delta T \tag{3}$$

The linear relationship between Brillouin frequency shift and temperature change will be used to calibrate temperature for sketching the trend of temperature change with time. Actually the relative change of temperature is more important than the real absolute temperature.

2.2 Interaction principle of seepage flow and temperature field

The thermohydraulic behavior in an embankment is complex. There are three sorts of basic thermal processes, heat conduction from the embankment crest and from the foundation due to geothermal flow, advection and radiation. The first two processes are partly coupled to each other because viscosity and density are temperature-dependent. A dynamic temperature field will form in the embankment with the interaction of seepage flow and temperature field. Temperature affects seepage flow, while seepage flow affects temperature field, respectively[9]. The problem is further complicated by the variation in material properties in the embankment, and the different conditions in the saturated and unsaturated parts of the embankment. The temperature in an embankment may vary seasonally due to the temperature in the air and in the upstream river or reservoir. For an embankment with height in excess of 10 meters, the influence from the air is however less than 1 ℃. In this case, the influence from the air remains therefore negligible[10]. Moreover, the indoor temperature is assumed to be constant. Therefore, the influence of radiation to embankment temperature can be ignored in the experiment. However, the advection is more effective than heat conduction in sand. Research shows, for a velocity as low as $10^{-7} \sim 10^{-6}$ m/ s, Darcy flow, the total heat conduction will mainly due to the advective part. In this case, the temperature distribution is mainly affected by the temperature of the water flow. The water pressure can be tested by using pore pressure tube; a thermo-advection model is shown in fig. 3. The energy flux consists of heat conduction in the solid phase and in the water, heat advection with the average leakage water flow, and dispersion due to variability in the leakage water flow velocities. An energy balance equation can be written [11]:

$$C_0\frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left\{\kappa\frac{\partial T}{\partial x_i} - C_w T q_i - Q_i^{disp}\right) \tag{4}$$

where C_0 is the volumetric heat capacity of thin sand, J/m^{3}K; C_w is the volumetric heat capacity of water, J/m^{3}K; Q_i^{disp} is the energy flux due to mechanical and thermal dispersion, J/m^{2}s; q_i is the leakage flow (Darcy seepage), m/s; T is the temperature, ℃; t is the time, s; x_i is the coordinate, m; κ is the thermal conductivity of thin sand, W/mK.

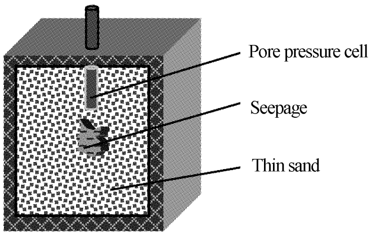


Fig. 3 Thermo-advection model in embankment

The temperature of water in seepage flow different to pore water acts as a tracer, but it propagates with the thermal velocity instead of the pore velocity. Tracers can not be assumed to be conservative here. So the general equation of seepage water can be described by Darcy law:

$$q_i = -\frac{k_{ij}}{\mu}\left(\frac{\partial p}{\partial x_j} + \rho_f g_i\right) \tag{5}$$

where k_{ij} is the permeability, m^2; μ is the dynamic viscosity, kg/ms; p is the pressure, N/m^2; g_i is the gravity, m/s^2.

The equation of motion for the leakage water flow and for steady state conditions can then be written as:

$$\frac{\partial}{\partial x_i}\left(k_{ij}\frac{\partial p}{\partial x_j} + \rho_f k_{ij} g_i\right) = 0 \tag{6}$$

Eq. (6), with initial and boundary conditions, describes the leakage water flow induced by differences in pressures and by differences in density of the water. As both the density and viscosity of the water are dependent on temperature, the relation between hydraulic conductivity K, m/s and permeability k, m^2, is:

$$K_{ij} = \frac{g\rho_f}{\mu}k_{ij} \tag{7}$$

A general solution of heat and water flow in an embankment is based on eqs. (4) and (6) in combination with initial and boundary conditions. The equations are coupled, as eq. (6) depends on the temperature field while the second and the third terms in eq. (4) depend on the flow field. For a specific embankment, it can be obtained by comparing the results with numerical simulations and measurements.

3 Design of simulation and monitoring system for seepage flow

A seepage simulation and monitoring system is designed and presented here below. This system consists of three parts: a seepage simulation cell, a control cell and an optical fiber demodulation cell, shown in fig. 4. An embankment model with a simulated seepage flow is shown in fig. 5(a). fig. 5(b) illustrates a section of embankment model with a seepage and the configuration of the sensing cable.

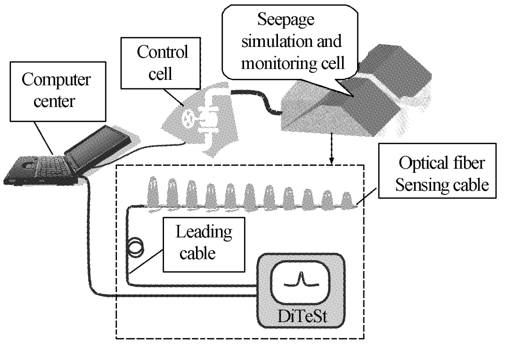
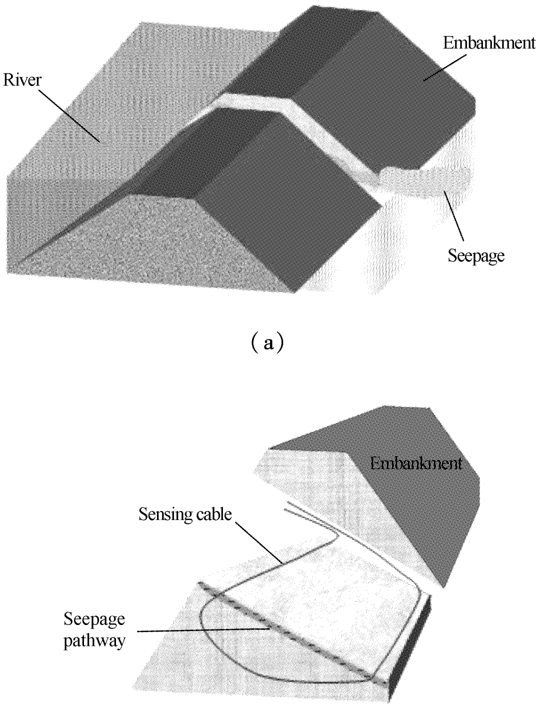


Fig. 4 Structure of simulation system



(a)

(b)

Fig. 5 Configuration of simulation cell and sensing cable

3.1 Simulation and control cells

The seepage pathway is simulated by natural and artificial ways, one is to embed in advance a zincificated steel tube in the embankment model, which simulates a bigger piping. The other is to pour water into the embankment by an extended tube, which is placed in the middle of the embankment. A pore pressure tube is installed and arrived to the upper part of this water tube to test the pressure of seepage water. The velocity of seepage water can be controlled by a control-valve and computer instructions. It is a closed loop control using PID servo system, shown in fig. 6.

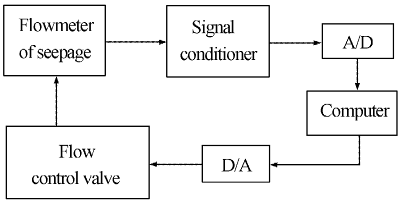


Fig. 6 Control structure flow

The seepage velocity can be tested using flowmeter. Conditioner circuit can filter the signal from common-mode interference. After the transfer from A/D and D/A, the signal will be input into the computer centre and the value of flux can be displayed. When setting a flux, this set value will be sent to a dedicated computer program to simulate the PID servo system[11-12]. The opening of the control valve gate will then be calculated accurately according to these informations. PID control for water flux is shown in fig. 7.

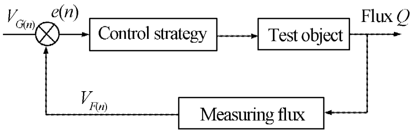


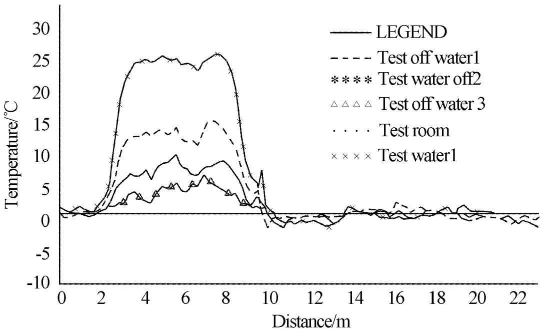
Fig. 7 PID control for water flux

Flowmeter is made up of impeller and photoelectric components. Flow flux can be transferred into a linear signal of 0 ~ 5 V DC and output to the computer. KVHV electronic electro-motion adjusting ball-valve is employed There is a "V" shape cut in the valve spindle, which can accept 4 ~ 20 mA DC or 1 ~ 5 V DC voltage as control signal and is controlled by single phase power owing to the linearity relation between the open angle of valve gate and input signal.

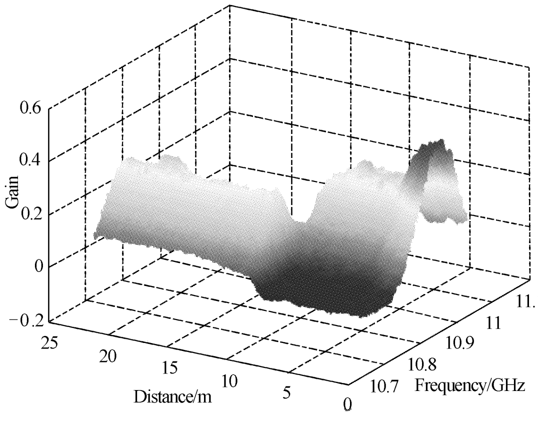
3.2 Demodulation Cell

The demodulation of sensing signal is performed by the Omnisens DiTeSt-STA201 analyzer[12]. Its temperature resolution is 0.1 ℃, accuracy is 1 ℃ and spatial resolution is 1.0 m. A higher spatial resolution of 0.5 m will need more time for a longer distance[13]. By adding DRR, test distance can be extended up to 250 km with almost no loss on measurement property and long-term stability. Using different temperature sensing cables, the measurable range of temperature is −270 ~ +700 ℃. Five groups of experiments with field sensing cables have been carried out. The sensing cable consists of two parts, the beginning part is communication fiber, and the end is field-used sensing cable. Field sensing cable was put into hot water firstly, after several minutes the cable was taken off water and measured at different interval.

The experiment results are shown in fig. 8. fig. 8(a) shows the temperature curves along sensing cable under different conditions. fig. 8(b) shows 3D-surface representing the overall information obtained from the gain traces related to all the different frequencies addressed during the spectral scan.



(a) Temperature curves of measurement



(b) 3D-surface information during the spectral scan

Fig. 8 Measurement results

3.3 Software for the monitoring system

The software system is written with Borland C + + and MATLAB, which is an important part in seepage monitoring and alarm system. The main menu of the system can design all sorts of work and report forms. In the flow flux submenu, the seepage flow can be read. After obtaining curves of the flow flux of the seepage during the measuring period, a trend of temperature change can be sketched. Seepage scales can be controlled by computer programs. One is manual control by selecting submenu to set the seepage flow; it is performed depending on PID optimization from the feedback signal. The other is to input the delay time T and the required flow flux Q. The computer can automatically adjust the parameters T and Q. The data will also be recorded and stored during the monitoring process, which is used to compare the results between the obtained data and those from DiTeSt analyzer.

4 Summary

The mechanism of the temperature change induced by seepage in an embankment has been analyzed. The measurement principle of stimulated Brillouin scattering distributed fiber temperature sensing system has been introduced. We construct a seepage simulator rig and monitoring system, including its software and control system. Simulation cell, control cell and demodulation cell have been proposed respectively. Simulator rig can be further extended to simulate longer embankments. Different conditions and boundaries can be simulated using this simulator rig. In addition the same type of seepage can be repeated to grasp important parameters, which is helpful to design an optimization configuration of sensing cables for real projects.

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