Research on the Early Warning Method of Water Delivery Pipeline Detonation Based on High-frequency Water Pressure Monitoring

Zhu Xinmin¹,², Lin Tianxiang³, Feng Shaokong³, Shang Feng¹,² and Fan Zhe¹,²
1 China Institute of Water Resources and Hydropower Research, Beijing, 100038, China
2 State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, Beijing, 100038, China
3 Shanghai Jiao Tong University, Shanghai, 200240, China

E-mail: zhuxm8@iwhr.com

Abstract: In order to study a novel monitoring method suitable for pressure water conveyance project, the fiber grating pressure sensor was adopted for monitoring the water pressure of in-service glass fiber reinforced plastic mortar pipeline. An emptying valve was used in the prototype test to simulate the leakage process and the dynamic water pressure process was recorded effectively by the fiber grating pressure sensor with high frequency and high precision. According to prototype test results, a fluctuation analytical method was proposed, which uses random average pressure as the equilibrium standard value. Meanwhile, an early warning system against pipe failure was developed based on this method. The system was verified by the simulated leakage tests, and the results show that the system could alarm the leakage of more than 0.25% of pipeline design flow, and the positioning accuracy was 10 m–20 m.

1. Introduction
Glass fiber reinforced plastics mortar pipes have the advantages of light weight, easy installation, corrosion resistance and low roughness coefficient of inner wall, and are widely used in urban water supply and drainage system [1, 2]. However, the massive application demonstrated that when glass fiber reinforced plastics mortar pipes are used in actual pressure water pipeline, there are phenomenon such as excessive deformation, local leakage and even pipe failure due to the multiple factors, including pipe material, engineering design, construction and management [3, 4]. Once the pipe failure occurs, it will not only cause waste of the water resource and affect the water consumption of urban residents, but also cause problems such as road collapse and buildings damage. Therefore, in order to ensure urban water supply safety and reduce economic losses and waste of resources, it is necessary to carry out safety monitoring and research of early warning against pipe failure for established pressure water conveyance project with glass fiber reinforced plastics mortar pipes.

With the development and improvement of data acquisition and monitoring system, several monitoring methods such as radar detection method [5], negative pressure wave method [6, 7] and mass balance method [8] have been widely used. Among these methods, inner water pressure is a
common and important monitoring indicator in pipeline waterworks. Some research demonstrated that there is a process of crack propagation and leakage increasing before pipe failure [9]. Once the pipeline leakage occurs, the inner water pressure changes immediately and the reaction velocity is very fast. Therefore, understanding the development process of pipeline leakage by monitoring the inner water pressure is conductive to realizing early warning against pipe failure and doing a good job in emergency response. Based on the flow equation of pipeline fluid and differential evolution algorithm, ZHANG et al. [10] estimated the pressure value along the pipeline and compared with real-time flow and pressure data, so as to achieve the purpose of determining pipeline leakage. Sadeghioon et al. [11] conducted laboratory and field tests and developed an intelligent method of monitoring pipeline leakage based on the indirect pressure change in pipe. TAO et al. [12] compared the change of pressure value at pressure monitoring points before and after pipe failure, drew the pressure drop isogram of pipe failure by calculating differential pressure, obtained the pressure variation mode of each monitoring point under leakage and non-leakage conditions, and located the bursting point through the pressure drop center. However, these conventional methods based on monitoring fluid pressure changes have low accuracy and frequency, and it is hard to capture the dynamic change process of inner water pressure when the pipeline leakage occurs in the water conveyance state, which greatly reduces monitoring effect and is prone to underreporting and misreporting. In recent years, fiber grating sensor technology develops rapidly in structural health monitoring, which is especially suitable for real-time dynamic monitoring of long-distance buried pressure pipelines [13, 14]. Fiber grating sensor overcomes the technical restriction of traditional leak detection methods [15–17], which reflects the variation of physical quantity to be measured by using the wavelength change of reflective (or transmissive) spectra. The wavelength of optical reflective (or transmissive) spectra is related to the grating period and the effective refractive index of fiber core, which is very sensitive to the change of strain (stress) and temperature. In addition, the measurement accuracy and frequency of fiber grating sensor are significantly higher than those of differential-resistance sensor and vibrating wire sensor commonly used in dam safety monitoring. Carrillo et al. [18] proposed a distributed fiber optic sensor to monitor oil leakage based on the characteristics that optical fiber will cause light intensity attenuation when bending and deforming, and monitored the changing position of light intensity by optical time domain reflectometer, so as to locate the leakage. Based on the principle of Mach-Zehnder optical fiber interferometer, ZHOU et al. identified and located the invasion movement along the line by utilizing three single-mode optical fibers in the pipeline, which was successfully applied to the security monitoring of oil and gas pipelines with a length of about 35 km [19]. At present, the monitoring methods based on optical fiber sensor are generally realized by laying optical cables along the pipeline, and the leakage monitoring speed is slow. Therefore, in this study, the fiber grating pressure sensor was adopted to monitor the inner water pressure in pipeline to improve the leakage positioning accuracy and monitoring speed.

In this study, the optic fiber grating pressure sensor was laid in the actual pressure water pipeline to monitor the dynamic change process of inner water pressure during the simulated leakage and the pipeline leakage was simulated by adjusting the opening of emptying valve. Based on the test data, an early warning method against pipe failure that is suitable for pressure water pipeline was established, and corresponding analysis software was developed for practical engineering monitoring.

2. Prototype test to simulate the leakage of pressure water pipeline
2.1 Simulated leakage tests
Glass fiber reinforced plastics mortar pipes of a water conveyance project were taken as the prototype test section, which has a pipe diameter of 2.2 m and a working pressure of 0.3 MPa–0.6 MPa. There are several sets of systems in the prototype test of pipeline leakage, and the layout diagram of observation equipment is shown in Figure 1. Fiber grating pressure sensor was laid in the pipeline to achieve high-frequency water pressure monitoring, with a water pressure measuring
range of 1000 kPa, a modulation wavelength range of 1525 nm–1600 nm, and a measurement accuracy of 1 ‰ F.S. In addition, 12 water pressure meters were arranged at a distance of 20 m between upstream and downstream of the F17 emptying valve.

Figure 1. The layout diagram of observation equipment.

The equipment was installed during the maintenance period of water supply. Epoxy resin was adopted to bond water pressure meters and optical cables on the corresponding position on the inner wall of pipeline, and polyurea was adopted for waterproof protection. Optical cables exited from the adjacent vent valve and were connected to the monitoring room.

After water supply was restored, F17 emptying valve was used in conducting simulated leakage test. The test process goes as follows: the measured water pressure value in pipe was observed and the test started when the value was stable with the start time of the test recorded. The openness of F17 emptying valve was changed and the leakage flow was measured. Three working conditions were designed in the test with the openness of one, two and three turns, respectively. F17 emptying valve was closed when the water surface of the drain well was over the drain pipe to form submerged discharge. FT810-32 fiber grating demodulation instrument with 16 channels was adopted to collect data with the frequency of 100 Hz.

Figure 2. The layout diagram of observation equipment.

In order to measure the actual leakage flow under simulated leakage conditions, the flow measurement device in prototype observation was made according to field conditions, as shown in Figure 2. The PVC pipe with the length of 4 m and two water-level alarms were used to make
volume observation device, which was fixed in the drain well of the emptying valve. The distance between water-level alarms was $\Delta L$; after the simulated leakage test started, the time difference $\Delta t$ that the upper and lower alarms send out alarms caused by the rise of water level was recorded, and the average leakage flow was $q = A\Delta L/\Delta t$. Where, $A$ was the sectional area of the wet well of F17 emptying valve.

2.2 Test results
Figure 3–Figure 5 are typical dynamic pressure measurement results during the simulated leakage test. According to the Figures, when the emptying valve is opened, the inner water pressure decreases suddenly due to the water hammer effect locally formed in pipe, and then the inner water pressure gradually recovers under the supplementary function of upstream water, and the low frequency components of the pressure fluctuation in the pipe increase. The local pressure drop caused by the leakage is related to the openness of emptying valve. When the emptying valve is closed, the inner water pressure increases suddenly and gradually attenuates to normal pressure fluctuation range. This phenomenon reveals the mechanism of pipe wall vibration caused by inner pressure change when the leakage locally occurs in pipeline, based on which early warning against leakage can be made. It should be noted that the process of inner water pressure vibration after the emptying valve is closed is a by-product of simulated leakage test and cannot be used in guiding early warning of leakage.

![Historical measurement process curve](image)

**Figure 3.** The dynamic pressure change process with one turn effective opening of emptying valve.
(Time to open the valve: 15:33, time to close the valve: 15:36, leakage flow of 10 L/s)
Figure 4. The dynamic pressure change process with two turns effective opening of emptying valve. (Time to open the valve: 16:05, time to close the valve: 16:06, leakage flow of 58 L/s)

Figure 5. The dynamic pressure change process with three turns effective opening of emptying valve. (Time to open the valve: 17:03, time to close the valve: 17:04, leakage flow of 97 L/s)

3. Early warning methods against pipe failure based on dynamic water pressure monitoring

3.1 Early warning methods against pipe failure

The test results demonstrated that the early warning against pipe failure could be implemented according to sudden pressure drop or frequency change. Considering that the sudden pressure drop occurs before the frequency change and that the monitoring based on the change of pressure frequency needs to accumulate data for a longer time, the analysis of early warning against pipe failure was conducted in this study according to the dynamic sudden pressure drop, so as to quickly and timely acquire the information of pipeline leakage with no additional delay caused.

The test results indicated that the amplitude of sudden pressure drop in pipe was small within the range of 1–3 kPa and the recovery time was also short (<1 min), therefore, a fluctuation analytical method that uses random average pressure as the equilibrium standard value was proposed. Specific instructions are as follows:

(1) The current time was set as $t_0$, and $t_0$ was in the time period of $[t_1, t_1 + \Delta t]$ to calculate the
average water pressure $p_0$ in the time period of $[t_1, \Delta t, t_1]$. Because the recovery time of pressure drop in pipe was very short, $\Delta t = 1.0$ min was set.

(2) According to the real-time measured value $p_t$ of inner water pressure in the time period of $[t_1, t_0]$, $\Delta p = p_t - p_0$ was calculated.

(3) It was set that the leakage caused pressure drop and produced the limit value $Y_p$ of $\Delta p$. The number of times $N_i$ of $\Delta p < Y_p$ in the time period of $[t_1, t_0]$ was counted.

(4) The limit value $Y_n$ of $N_i$ was set, and the system would alarm when $N_i > Y_n$.

Two thresholds $Y_p$ and $Y_n$ were introduced, among which $Y_n$ is equal to the time of duration. However, neither $Y_p$ nor the time of duration $\Delta t$ was recommended to be taken as the threshold in the study. There are two reasons. On the one hand, the recovery time of pressure drop in pipe is very short, and it is hard to give a reliable limit value of $\Delta t$ through the test; on the other hand, the vibration signal of water pressure contains several frequency, and it is prone to underreporting and misreporting due to accidental excessive vibration signals in practical application if the limit value of $\Delta t$ is simply set.

3.2 Theoretical basis of early warning against pipe failure

To explore the change rule of $\Delta p$ and better select the values of $Y_p$ and $Y_n$, measured data were treated in the study, in which the $\Delta p$ in the period of $[t_1, \Delta t, t_1]$ were sorted from largest to smallest, and the distance of $\Delta p$ was taken as 0.1 kPa for cumulative probability statistics. The results are shown in Figure 6.

![Figure 6](image)

**Figure 6.** The distribution diagram of cumulative probability of $\Delta p$.

According to the rules in Figure 6, the cumulative probability with Gaussian distribution was taken for formula fitting, and the source formula is Equation (1).

$$P(Y_p) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{Y_p} e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx$$  \hspace{1cm} (1)

Where, $P(Y_p)$ is the cumulative frequency of $Y_p$; $\sigma$ is the standard deviation; $Y_p$ is the given limit value of $\Delta p$; $\mu$ is the average value.

During the measurement process, the data collection frequency was 100 Hz, so 6000 data were measured every minute. According to Equation (1), the theoretical value of the number of times $N_i$ of $\Delta p < Y_p$ in the time period is expressed as Equation (2).

$$N_i = 6000P(Y_p)$$  \hspace{1cm} (2)

All measured data were taken and the fitting results are shown in Figure 7. The fitting equation is Equation (3):
\[ P(Y_p) = 0.07868 \int_{-\infty}^{Y_p} e^{-\frac{(x+0.0633)^2}{0.5142}} \, dx \]  \tag{3}

Equation (2) was substituted into Equation (3), and the relational expression (4) of \( N_t \) and \( Y_p \) can be obtained.

\[ N_t = 4612.8 \int_{-\infty}^{Y_p} e^{-\frac{(x+0.0633)^2}{0.5142}} \, dx \]  \tag{4}

According to the warning condition of \( N_t > Y_N \), the relational expression (5) of \( Y_N \) and \( Y_p \) can be obtained.

\[ Y_N < 4612.8 \int_{-\infty}^{Y_p} e^{-\frac{(x+0.0633)^2}{0.5142}} \, dx \]  \tag{5}

According to different leakage flow, the least favorable condition, that is, the leakage flow \( Q \) is equal to 10 L/s, was selected as the warning condition. \( Y_N = 50 \text{ times/min} \) was taken, and \( Y_p < -1.321 \text{kPa} \) was obtained.

![Figure 7](image)

**Figure 7.** The fitting results of cumulative frequency with Gaussian distribution of measured data.

### 3.3 Conclusion and application of early warning against pipe failure

Based on the analysis of the data in prototype test, the warning threshold value was concluded in this study as following equation. The threshold could detect the leakage with the leakage with the minimum leakage flow of 10 L/s.

\[ \begin{align*}
Y_p & = -1.3 \text{kPa} \\
Y_N & = 50 \text{ times/min}
\end{align*} \]  \tag{6}

### 4. Development and verification of early warning software against pipe failure

In accordance with the above fluctuation analytical method, *PipeMonitoring* system of early warning system against pipe failure in pressure water pipeline was developed, which includes many modules such as real-time pressure analysis and early warning, review of historical pressure history curve, pressure history measurement report, and pressure early warning threshold setting. This software read the pressure data demodulated by the fiber grating demodulation instrument in real time, which were analyzed and judged, thus achieving the early warning against pipe failure. The reliability of early warning system against pipe failure was verified through the field simulation.
test. The test results are shown in Figure 8–Figure 10. The system could accurately alarm the leakage, and the alarm delay was within 1 minute.

**Figure 8.** One turn effective opening of emptying valve ($N_t = 376$ times/min).

**Figure 9.** Two turns effective opening of emptying valve ($N_t = 180$ times/min).

**Figure 10.** Three turns effective opening of emptying valve ($N_t = 2317$ times/min).
5. Conclusion
In this study, the optic fiber grating pressure sensor was laid in the pressure water pipeline and the pipeline leakage was simulated through the emptying valve to monitor the dynamic water pressure change process during the leakage. The research conclusions are as follows:

(1) The early warning against pipe failure could be implemented according to the sudden pressure drop or the frequency change caused by pipeline leakage. Dynamic monitoring of sudden pressure drop could improve the positioning accuracy and monitoring speed of leakage.

(2) When the leakage occurred in pressure water pipeline, the pressure in the pipe decreased quickly, and the decreasing amplitude was related to the leakage amount.

(3) The supplementary function of upstream water made the pressure drop in pipe gradually recover and the low frequency components in the pressure fluctuation in the pipe increase.

(4) In the study, a fluctuation analytical method was proposed, which used random average pressure as the equilibrium standard value. Meanwhile, a corresponding early warning system against pipe failure was developed based on this method. The system was verified by the simulated leakage tests. The results demonstrated that the system could make accurate warning of the leakage with the leakage flow larger than 10 L/s. The leakage flow was 0.25% of the pipeline flow, and the positioning accuracy was 10 m–20 m.

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