Field Test of Online Leakage Noise Monitoring for Pressure Water Pipeline

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Abstract: In order to study the applicability of leakage noise (vibration) monitoring method, an online leakage monitoring test was carried out on a large pipeline. In the test, the emptying valve on the pipeline was used to simulate the leakage point, and the vibration signal caused by leakage was monitored by the hydrophone and other floating cables installed in the pipeline. By controlling the opening degree of the emptying valve, the different degrees of leakage between 10L/s and 105L/s was simulated, and the monitoring data for 10 minutes were recorded from 5 minutes before valve opening. The analysis results of the test data showed that although the environmental background of the monitoring was very disturbing, the leakage could be detected when the leakage degree was more than 0.05% of the pipeline flow. The monitoring results also showed that the noise caused by the leakage of large buried water pipelines was mainly transmitted in the form of vibration along the soil around the pipeline.

1. Introduction

For a long time, the uncoordinated development of social economy and ecological environment has come at a cost in China. Especially water resources problems are becoming increasingly acute, such as water resources shortage, serious water pollution and water ecological degradation. To improve this situation, many large-sized water transfer projects have been developed in recent years, including North Hubei Water Transfer Project and Hanjiang-to-Weihe River Project. Such projects have significantly improved the construction of water ecological civilization, but hidden dangers inevitably exist in some parts after the completion of the project due to its large construction scale and fast progress, which even causes disasters. Among them, pressure water pipeline accidents represented by
Pipe failure are the most frequent. In 2015, a total of 178 various pipe failures happened in China [1], causing enormous economic loss and serious social impact.

There are two forms of pipe failures, namely burst-mode form and progressive form. The former is caused by water hammer effect [2] or piping blockage with low occurrence probability, and can be effectively avoided by existing technological means and standard management. The latter is developed from pipeline leakage, which is hard to be avoided because of complex causes. The formation of progressive pipe failure goes through three stages, that is, stabilization stage, transitional stage and saltational stage. When it goes into the saltational stage, the leakage flow increases abruptly, the pipeline bursts and is disintegrated, and there is no need for maintenance, so the transitional stage is the key stage for prevention and control of pipe failure. At present, the main methods for monitoring the leakage of pressure water pipeline are flow monitoring method [3], negative pressure wave method [4, 5], pipeline monitoring by distributed fiber optic sensing [6–8] and noise monitoring method [9, 10]. All of these methods have some disadvantages, which greatly reduces the validity of monitoring results. For example, the negative pressure wave method is weak in anti-interference and prone to underreporting and misreporting; the sensitivity of flow monitoring method and its positional accuracy for leakage point are relatively low; the pipeline monitoring by distributed fiber optic sensing requires embedding monitoring devices such as optical fibers on the outer wall of the pipeline, which is applicable to the completed water pipeline; and the noise monitoring method is rarely used for leakage monitoring on long-distance water pipeline due to rapid noise attenuation, generally monitor the noise in a short distance with the buried depth of 1–2 m. Therefore, it is urgent to carry out basic research on related application to lay a foundation for future research and development of early warning system of pipe failure that is suitable for long-distance large-diameter pressure water pipeline.

Leakage signals are mainly composed of water howling sound wave and abnormal pipe vibration. Howling sound wave belongs to aerodynamic noise, and is formed by air vertex and air shock led by fluid or disturbance caused by sudden pressure change during leakage. However, abnormal pipe vibration noise is caused by the pressure pulsation in pipeline or the mechanical vibration generated by fluid with pipeline and solid medium around pipeline [11]. Generally, aerodynamic noise and vibration noise occur at the same time and interact with each other in the process of transmission. Since the frequency of vibration noise is lower than that of aerodynamic noise, the high-frequency components of the signal have been basically attenuated after the signals transmit in the water, so the retained signals are mainly vibration signals of low-frequency components.

In terms of signal analysis, many statistical methods have been proposed to predict pipe failure, such as Poisson generalized linear model [12], the proportional hazard model [13], harmonic analysis method [14, 15] and so on. A brief summary of the pipe failure prediction models can be found in the literature [16]. These models are indeed of some practical value in analyzing whether the pipeline failures. However, the specific degree of pipeline damage when the pipeline leakage occurs cannot be quantitatively estimated. The fact shows that it is necessary to make accurate judgment on the degree of pipe failure, so some correlational researches are also carried out.

This study focuses on the phenomena that pipeline leakage leads to vibration, and online field monitoring test was carried out for the water pipeline of a project in Shenzhen. To achieve the goal
of long-term continuous monitoring of pressure pipeline, the hydrophone was installed in the pipeline to monitor the leakage signal, and the leakage severity and position were judged by analyzing the signal characteristics, so as to achieve the purpose of pipe failure forewarning. This method is applicable to both newly-established pressure water pipeline and completed pressure water pipeline. The monitoring is not affected by buried depth, and it is also convenient for the maintenance and reconstruction of the monitoring system.

2. Leakage monitoring principle of pressure pipeline

From the mechanism of radiating acoustic waves, the noise source can be divided into three categories of monopole source, dipole source and quadrupole source. Such sources are formed by non-uniform mass or heat flowing into the medium. In 1950s, Lighthill first proposed the acoustic analogy theory for the aeroacoustic problem [17, 18], and proved that the noise source in free space is quadrupole source and the leakage sound power is proportional to the eighth power of its velocity. However, Curle [19] further considered the influence of static boundary, and emphasized that when there is a solid static boundary, the leakage sound power is proportional to the sixth power of its velocity, representing the characteristics of dipole source. The vibroacoustic problem is rarely studied in previous research, and is analyzed by the numerical computing method. However, the research of MAO et al. [20] shows that the acoustic analogy theory is a universal theory to analyze the noise generation mechanism and has a good application in monitoring the aerodynamic noise and vibration noise. At the same time, the research of Howe indicates that the generation principle of all sound sources can be attributed to aeroacoustic problems [21]. Therefore, the acoustic analogy theory can also be used in this study to discuss the monitoring principle of vibration noise.

The leakage process of pressure pipeline relates to fluid-solid coupling, and the interaction between fluid and pipeline is very complex. During the leakage process, when the leakage degree is small, the fluid-solid coupling effect between the water and pipe wall or soil outside the pipe is significant, and the noise source shows more dipole source characteristics. With the increase of leakage degree, the pipeline pressure will slightly decrease, the boundary effect of the pipeline will decease accordingly, and the characteristics of quadrupole source will gradually appear. Similarly, it is pointed out in Reference [22] that the leakage acoustic source is actually composed of the dipole source of the wall and the quadrupole source of Reynolds stress. It follows that the characteristics of dipole source and quadrupole source should also be considered in concluding the laws of noise source. In addition, the leakage sound power collected tended to be small because the noise was bound to decay in the water environment, so the actual leakage sound power was not simply proportional to the sixth or eighth power of its velocity.

Considering the above situations, the corresponding theoretical model was established in this study. It is supposed that the leakage sound power is proportional to the n-th \((6 \leq n \leq 8)\) power of its velocity, and the proportionality coefficient \(K\) is introduced, that is,

\[
P_w = K \frac{\rho^2 V^n d^2}{\rho_0 C_{n/3}}
\]

(1)

Where, \(V\) is the leakage velocity of the fluid; \(\rho\) is the fluid density of mixed medium at the leakage spot (it is smaller than that of water due to the inclusion of gas in the fluid); \(\rho_0\) is the initial density
of the fluid; \(C_0\) is the local sound velocity; \(d\) is the size of leakage bore.

Supposing that the fluid density and local sound velocity are stable, Equation (1) can be further simplified to obtain.

\[
P_w = \eta V^n d^2 = \lambda V^n S
\]  \hspace{1cm} (2)

Where, \(\eta\) and \(\lambda\) are the constant coefficients; \(S\) is the area of leakage bore and is proportional to the square of leakage bore size.

In addition, the leakage flow \(Q\) is equal to the product of leakage bore area \(S\) and velocity \(V\), that is,

\[
Q = VS
\]  \hspace{1cm} (3)

So, it can obtain that

\[
P_w = \lambda V^n S = \lambda V^{n-1} Q
\]  \hspace{1cm} (4)

Where, \(\eta\) and \(\lambda\) are constant proportionality coefficients; \(Q\) is the leakage flow.

According to the Bernoulli’s equation, it shows that

\[
\Delta P + \frac{\rho_0 V_0^2}{2} + \rho_0 gh = \frac{\rho V^2}{2}
\]  \hspace{1cm} (5)

Where, \(\Delta P\) is the pressure difference before and after pipeline leakage; \(V_0\) is the descending speed of liquid level in the pipeline; \(h\) is the height of the fluid level.

Since the large pressure water pipeline is the research object in the study, the descending speed of liquid level in the pipeline \(V_0\) is very small, which is ignored.

\[
V^2 = \frac{2}{\rho} (\Delta P + \rho_0 gh)
\]  \hspace{1cm} (6)

Moreover, the leakage sound power \(P_W\) is proportional to the square of the amplitude \(A\), and coefficient \(\mu\) is introduced, that is,

\[
P_w = \mu A^2
\]  \hspace{1cm} (7)

Equations (4), (6) and (7) are combined to obtain

\[
A^2 = \frac{\lambda}{\mu \rho} \left( \frac{2}{\rho} \right)^{n} \left( \Delta P + \rho_0 gh \right)^{n-1} Q
\]  \hspace{1cm} (8)

In pipeline leakage, the pressure difference between the pressure inside and outside the leakage bore is dynamic, which makes it difficult to judge the pressure difference intuitively and effectively. Considering the actual situation of the project, the pressure change caused by leakage in large pressure water pipeline is relatively small, and the operation pressure \(F\) of the pipeline is approximately equal to \((\Delta P + \rho_0 gh)\), so the operation pressure \(F\) of the pipeline was considered as an evaluation indicator to discuss in this study.

It is set that

\[
F = \Delta P + \rho_0 gh
\]  \hspace{1cm} (9)
Equation (9) can be converted into

\[ A^2 = \frac{\lambda}{\mu} \left( \frac{2}{\rho} \right)^{\frac{n-1}{2}} F^{\frac{n-1}{2}} Q \]  

(10)

Expression (10) shows that there is a power function relationship between the amplitude \( A \) and leakage flow \( Q \) and between that and operation pressure \( F \). If the operation pressure \( F \) is constant, the amplitude \( A \) is proportional to the \( \frac{1}{2} \) power of the leakage flow \( Q \). This exponential relation reflects that during the leakage process, the amplitude of leakage signal continuously increases with the increase of leakage flow, but the amplification gradually decreases and finally tends to be stable.

When the leakage flow \( Q \) is constant, the amplitude \( A \) is proportional to the \( \frac{(n-1)}{4} \) power of the operation pressure \( F \), and the power value is always larger than 1, indicating that the amplitude of leakage point increases with the increase of operation pressure, and the amplification continuously increases until the pressure pipeline fails. Such laws reflected in Expression (10) are quite consistent with the leakage characteristics of pipelines. At the initial stage of pipeline leakage, the pipeline damage is relatively light, and the increase of pressure and leakage flow will cause irregular pulsation of turbulent flow field at the leakage bore, which will lead to intensified friction between the fluid and the pipe wall, and the amplification of leakage signals obtained by monitoring will naturally increase continuously. However, when the leakage flow increases to a certain degree, the operation pressure will also decrease due to pipeline damage, which will cause the amplitude of the leakage signals to eventually stabilize.

The logarithms of the two sides of Expression (10) are taken, and it is obtained after summary that

\[ \log_{10} A = \frac{n-1}{4} \log_{10} (FQ^{n-1}) + \frac{1}{2} \log_{10} \left( \frac{\lambda}{\mu} \left( \frac{2}{\rho} \right)^{\frac{n-1}{2}} \right) \]  

(11)

To explore the undetermined coefficient in Equation (11), indoor simulation experiments and studies were conducted. The indoor experimental data are adopted for fitting the function of several variables, and the empirical formula of amplitude \( A \) with leakage flow \( Q \) and operation pressure \( F \) is obtained.

\[ \log_{10} A = 1.35 \log_{10} FQ^{\frac{1}{2}} + 2.83 \]  

(12)

Equation (12) is further explained that all physical value units were SI units, and \( n=6.4 \) was obtained from above equation, which indicates that the fluid-solid coupling effect in leakage process was significant and the noise source was mainly dipole source.

When the pipeline was monitored, the pipeline leakage accident could be determined as long as the amplitude of signals increased rapidly. At this time, the operation pressure and corresponding amplitude were substituted into the empirical formula to estimate the leakage flow, so that the corresponding measures could be taken for the damaged pipeline according to the leakage flow to achieve the purpose of effectively preventing pipe failure.

3. Test summaries

3.1 Layout of sensor

The filed monitoring test was carried out on the buried pressure pipeline of a water supply project in
Shenzhen. As shown in Figure 1, the pipeline with the length of about 450 m and inner diameter of 2 m was selected in this test. The pipe joint was mainly composed of FPR sand-filled pipes except for some parts which were made of steel pipes. Air evacuation valves A25 and A26 on the pipeline were used for outlet power cable, and an emptying valve E17 was placed at the middle of two air evacuation valves. The emptying valve was connected with the vertical manhole. The condition of pipeline leakage was simulated by adjusting the opening degree of the emptying valve. At the same time, 12 hydrophones were arranged along both sides of the pipeline with the emptying valve as the center, and the spacing of the hydrophones was 10 m.

![Figure 1. Schematic diagram of field on-line test.](image)

### 3.2 Sensor and data collecting instrument

The vibration transducer used in this test was hydrophone, which was composed of piezoelectric ceramic pressure-sensitive elements and electronic circuits that were sealed in a soft plastic tube filled with kerosene. The external shape is cylindrical to reduce vortex vibration. During monitoring, various vibration signals were coupled to pressure-sensitive elements in the form of pressure fluctuation through the water in the pipeline and kerosene in the hydrophone, and then transmitted to the data acquisition unit by electrical signals for analog-to-digital conversion and recording. In making hydrophone cables, the density of various materials shall be fully adjusted to ensure that the overall density of the cable is the same as that of water. Small seismograph Geode and laptop produced by American Geometrics Company was adopted for data acquisition. Geode is a high-precision broadband analog-to-digital conversion and data transmission unit, which can complete data acquisition, transmission and recording through computer control. The data acquisition module is connected with the GPS receiver through a computer, and GPS satellites provide standard time signals, thus achieving continuance data acquisition. The time interval of data acquisition was set as 0.125 ms, that is, the sampling frequency was 8000 Hz. Standard format (SEG-2) of geophysical exploration industry was adopted by Geode for recording. The maximum record length (the number of data in each channel) of each data field was 65,536 data, which was approximately equivalent to 8.192 s. The titles of data fields were automatically generated according to the time order of acquisition. The
technical indexes of the sensor and recorder are shown in Table 1.

| Name          | Form                                      | Technical index                        |
|---------------|-------------------------------------------|----------------------------------------|
| Hydrophone    | Piezoelectric ceramic acceleration type   | Frequency response: 4–5000 Hz          |
| Seismograph   | Geode-24 channels                         | A/D conversion: Δ–Σ mode 24 bit        |
|               |                                           | Frequency response: 1.75–20000 Hz      |

### 3.3 Test conditions

In the field test, the operation pressure of the pipeline was controlled as 0.25 MPa. When the water pressure and velocity in the pipeline were basically stable, the leakage simulation test was carried out at different opening degree of the emptying valve. The emptying valve can be adjusted for a total of 53 rounds from fully closed to fully open. Through practice, three cases have been completed, namely, the emptying valve was opened to 1 round, 2 rounds and 3 rounds, respectively. The leakage degree (flow) corresponding to each case is shown in Table 2. The test time for each case was about 10 min, 5 min of which was to collect the data under the condition before opening (corresponding to no leakage) and 5 min of which was to collect the data under the condition after opening.

| Number of valves opening rounds | 1 round | 2 rounds | 3 rounds |
|---------------------------------|---------|----------|----------|
| Flow (L/s)                      | 10.34   | 34.96    | 68       |
| Leakage degree                  | 0.05%   | 0.16%    | 0.32%    |

### 4. Test data analysis and results

#### 4.1 Methods of data processing

There are multiple sets of electricity transforming facilities and large plants around the test site, which is located in the traffic artery, and there is strong disturbance vibration in the environment. Meanwhile, 50 Hz AC induction generated by leakage monitoring device also has serious influence on the data. Therefore, noise suppression is the primary task of data processing, which was achieved mainly through the tuning bandpass and 50 Hz and high order harmonic notch filter. To highlight the vibration signal caused by leakage, spike deconvolution process was carried out for the data after noise suppression, and continuous vibration signals were converted into sharp pulses to facilitate signal identification.

Figure 2 shows the recorded data after 50 Hz notching, in which the vibration signals caused by leakage could hardly be identified. Fig. 3 shows the results after further filtering. It can be seen that there are events formed by two groups of waves, which intersect between hydrophone H12 and hydrophone H13, indicating that the source of wave is located between hydrophone H12 and hydrophone H13, that is, the position of emptying valve E17. However, the signal-to-noise ratio of
data in Figure 3 is very low, which is not conducive to the identification of pipeline vibration caused by leakage. Figure 4 is the result of the data in Figure 3 after spike deconvolution process. Deconvolution is a common processing method in seismic reflection data processing. The processing can make the energy of the signal form a pulse to the greatest extent, which is conducive to improving the resolution and signal identification. Through the comparison between Figure 3 and Figure 4, it is found that after spike deconvolution process, the signal energy concentrated on a certain time and formed a sharp pulse wave that was easily to be identified.

**Figure 2.** Recorded data after 50 Hz notching.

**Figure 3.** Recorded data after the bandpass filter.
4.2 Results of data processing

The processing results of monitoring data under each condition are shown in Figure 5–7.

Figure 5 shows the processing result of monitoring data when the emptying valve opened for 1 round (the leakage flow is 10.34 L/s). From Figure 5, strong amplitude of wave appears in the period of 0–0.5 s, and events intersect between H12 and H13 hydrophones. It can be known that there was an excitation source, that is, the leakage point. According to the calculation, the leakage point was around 113 m, and the positioning error was about 1.5 m. Compared with the background noise, the wave did not take an absolute advantage, but above analyses still fully demonstrated the effectiveness of this method. In addition, when the leakage degree was not larger than 0.05%, the pipeline damage was not enough to affect the pipeline operation for large buried water pipeline. The pipeline leakage could be monitored when the degree was 0.05%, which proved that this method required the universality in the monitoring of pipeline engineering.

Figure 6 and Figure 7 show the processing results of monitoring data when the emptying valve opened for 2 rounds (the leakage flow is 34.96 L/s) and 3 rounds (the leakage flow is 68 L/s), that is, the processing result when the leakage degree is 0.16% of the leakage flow. From Figure 6 and Figure 7, strong amplitude of wave also appears in the period of 0–0.5 s. Due to the increase of leakage flow, the wave is more prominent in background noise compared with that under the condition that the emptying valve is opened for 1 round. The events of wave also intersect between H12 and H13 hydrophones. The leakage point could be figured out and the positioning error was about 1 m. Besides, the waveform frequency close to the leakage point was obviously higher.
4.3. Analysis of fluctuation propagation path

Pressure water pipeline water in pipeline and strata around the pipeline formed a complex medium system. When there was a leakage somewhere in the pipeline, the vibration caused by the leakage propagated to all sides in the form of fluctuation. There are basically three ways of propagation, namely, along the pipe wall, along the water body and through the soil around the pipe. Different propagation paths have different propagation velocity and attenuation property, and the vibration received at the observation site may be the result of mutual coupling of various path fluctuations. By analyzing the propagation velocity of the wave, the propagation path of the wave could be determined to provide basis for accurately locating the leakage point. Figure 8 shows the propagation-time history relation of leakage signals when the leakage flow is 0.32%. It can be calculated that it took 0.211 s for the wave to propagate from H1 hydrophone to H12 hydrophone with the distance of 110 m, so the propagation velocity of the wave was about 521 m/s. Generally speaking, the propagation velocity of the wave in water is about 1480 m/s, and it is larger along FPR sand-filled pipe. In addition, the test section is composed of multiple sections of 7.6 m FPR sand-filled pipes, and the rubber seal ring was used for the socket, which has the function of vibration isolation and wave absorption. Therefore, it can be inferred that the wave mainly propagated along the soil around the pipe. At the same time, the compressional wave velocity in the soil was generally larger than that in water in general, so it can be further judged that the hydrophone received Rayleigh wave generated by vibration.
In this study, the online monitoring test was carried out by utilizing the water pipeline of Water Sources Project in North Shenzhen, and pipeline leakage accident was simulated by adopting the emptying valve. Following conclusions were drawn.

1. The relation among the operation pressure, leakage flow and amplitude of leakage signal was deduced in this paper. Under the condition that a single variable was kept, the amplitude of leakage signal increased with the increase of operation pressure of the pipeline; as the leakage flow increased, the amplitude of leakage signal increased, but the amplification gradually decreased and finally tended to be stable.

2. The empirical formula of operation pressure, leakage flow and amplitude of leakage signal was

\[ \log_{10} A = 1.35 \log_{10} F Q^{2/7} + 2.83 \]

At the same time, \( n \approx 6.4 \) was obtained from the formula, which indicates that the fluid-solid coupling effect in leakage process was significant and the noise source was mainly dipole source. According to the empirical formula, the leakage could be estimated by using the pipeline operation pressure and the read amplitude during monitoring.

3. Although the field background noise was very strong, the results demonstrate that the monitoring methods in the paper could effectively identify and locate the leakage flow above 10.46 L/s. The larger the leakage flow was, the more obvious the wave characteristics caused by abnormal vibration was. What’s more, the spike deconvolution process has remarkable effects in suppressing noise and improving the signal recognition.

4. The leakage noise was mainly transmitted in the form of vibration along the soil around the pipeline, which belongs to Rayleigh wave.

In the future, the data will be continuously analyzed to further analyze the relation of the leakage degree with the amplitude and frequency and the application in progressive pipe failure forewarning.

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