Deformation Inspection and Safety Assessment Method of Buried Flexible Pipeline in Service

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Abstract. The working performance of buried flexible pipelines is connected with the pipe-soil interaction; the weak stiffness of backfill leads to large long-term pipeline deformation and even structural failure. Spangler’s formula is a theory for macroscopic evaluation of pipeline deformation, which cannot reflect the deformation state of various parts around the pipe from a microscopic view. A large number of engineering practices have shown that when the macro radial deformation of the flexible pipe is not large, it is also possible that the local geometric size of the pipeline may change suddenly in the microscopic view. Combining with a diversion project, a laser scanning and piecewise elliptic curve fitting combined method was proposed to measure the empty pipeline deformation in this paper. The deformation pattern of the flexible pipeline was analyzed. And then, the analysis results were verified by the elastic wave test and material test data. Based on the deformation inspections, the internal force and related reliability of pipe structure were calculated. Finally, the structural safety of each pipe was assessed to guide the replacement, repair and reinforcement of pipeline.

1. Introduction
With the rapid development of polymer materials technology, large-diameter flexible pipes, represented by FRPM, have the advantages of corrosion resistance, low roughness, light weight, high strength, convenient installation and economic investment, and are widely used. However, in recent years, the pipe failure of pressure water pipeline occurs frequently, involving all kinds of large-diameter pipes, especially the large-diameter buried flexible pipeline. Scholars systematically sum up the application experience of FRPM in pressure water diversion projects and think that the compactness of backfill on the side of the pipe is the main factor affecting the structural safety of FRPM pipelines [1], and the pipe material is another important cause of accidents [2]. At present, there is no safety assessment standard for large-scale buried flexible pressure water pipelines at home and abroad, so how to clarify the influence of these two factors in practical engineering is a problem that must be solved in the safety assessment of large-diameter buried pipelines.

The structural design of flexible pipeline at home and abroad is based on Spangler’s formula [3] [4]. The basic premise of Spangler’s formula is that the earth pressure outside the pipeline is distributed symmetrically along the horizontal and vertical axes of the pipeline. If the settlement of the top of pipe is \( \Delta y=\Delta x \), the horizontal displacement of pipe wall is \( \Delta y=\Delta x/2 \), that is, the settlement
of the top of pipe is twice the horizontal displacement on the side of the pipe [5]. However, whether this assumption holds or not depends on the factors such as actual construction method, construction quality control and hydrogeological conditions of pipeline foundation. The proper use of Spangler’s formula for pipeline landfill design instead of pipe body design is crucial to ensure the safe operation of large-diameter flexible pipeline [6].

Combining with a diversion project, it is indicated in this paper that the working performance of pipeline structure did not always satisfy the Spangler hypothesis, so a laser scanning and piecewise elliptic curve fitting combined method was proposed to measure the deformation of empty pipeline. The deformation pattern of the flexible pipeline was analyzed, and the internal force and reliability index of pipeline structure were calculated according to the back analysis of measured deformation. Finally, the recommended standards for the safety classification of pipeline structures were given, which provided a feasible method for the safety assessment of large-diameter buried flexible pipelines.

2. Deformation inspection method of large-diameter buried flexible pipeline

2.1 Cross-section laser scanning method to detect pipeline deformation

At present, the laser range finder is widely used in deformation measurement of large-diameter buried pipeline to measure the radial compression deformation \( w \) of empty buried pipeline, which is the core index for controlling the long-term pipeline deformation and judging the safety state of pipeline in the design code of pipeline structure.

However, in practice, it is difficult to ensure that the laser emitted by the laser range finder just passes through the center of the pipeline and is perpendicular to the pipe wall, resulting in a large measurement error of \( w \). Therefore, the laser scanner was adopted in the detection of this project. The distance \( d_i \) and angle \( \theta_i \) from each point on the pipe wall to the rotation center were measured, and the coordinate system was established with the rotation center as the origin, so that the coordinates of each point on the pipe wall could be obtained by fitting calculation, as shown in Figure 1.

\[
\begin{align*}
  x_i &= d_i \cos \theta_i \\
  z_i &= d_i \sin \theta_i
\end{align*}
\]

(1)

Where, \( x_i \) and \( z_i \) represent the coordinates of each measuring point.

![Laser scanning detection of section in pipeline](image)

![Piecewise elliptic curve fitting](image)

**Figure 1.** Pipeline deformation inspection

Under the influence of tripod, there is a blind area in section scanning, and the scanning angle interval in actual measurement is \([0, \ 4 \pi/3] \cup [-\pi/3, 0]\). Since it is difficult to determine whether the rotation center is located in the center of the pipeline section, it is necessary to fit the shape of the pipe wall according to the coordinates of each measuring point, and further estimate the deformation...
of the pipeline. Under normal circumstances, a circular pipe is deformed into an elliptical pipe under external pressure. It is assumed that the symmetry axis of the ellipse formed by pipeline deformation is along the horizontal direction and the vertical direction respectively, the elliptic equation can be written as

$$Ax^2 + Bz^2 + Cx + Dz + E = 0$$

(2)

After data fitting, the standard equation of ellipse was obtained, with which the vertical axis length $2b$ and horizontal axis length $2a$ of the ellipse could be obtained. Therefore, the deformation of the top of pipe can be calculated as follows

$$w = D_0 - 2b$$

(3)

Where, $D_0$ is the inner diameter of the factory section of the pipeline. The deformation state of pipeline could be known by comparing $a$ and $b$. In this paper, the deformation state of pipeline was divided into two types: one is the case of $a > b$, which is the conventional deformation state of flexible pipeline, and the top of pipe is displaced downward due to the pressure of the upper soil layer; another is the case of $a < b$, and the result of $w$ is usually negative. At this time, the lateral compression force on the pipeline is large, which may be related to the high groundwater level, excessive compaction of soil on the side of the pipe, or the accumulation of heavy objects on the side of the pipe. Most of the pipeline deformation belongs to the case of $a > b$.

When the backfill on the side of the pipe is compacted, the deformation of the empty pipeline is vertically and horizontally symmetrical. The soil outside the upper half of the pipeline was in close contact with the pipe wall due to the dead weight, while the soil outside the lower half of the pipeline was not easy to backfill and compact, so the lower half of the pipeline was easier to deform. At this time, the deformation value calculated by Equations (2) and (3) may be smaller. Therefore, the elliptic curve was adopted to fit and analyze the points of the upper half and the lower half of pipeline, respectively, and the common midpoint and horizontal axis of the upper and the lower half ellipse were controlled, so the short axis $b_1$ of the upper half ellipse and that $b_2$ of the lower half ellipse could be obtained.

$$w = D_0 - (b_1 + b_2)$$

(4)

Where, when the lower part of the pipeline backfill is uncompacted, there is $b_2 < b_1$. However, because there are relatively few measuring points in the lower half of the pipeline and the fitting accuracy is relatively low, the opposite situation will occur. Therefore, in actual data processing, Equations (3) and (4) were taken to solve $w$ for the same group of data points, and the larger value was taken as the measurement result of pipeline deformation.

2.2 Deformation pattern of buried flexible pipeline

According to the fitting analysis results of large-diameter buried flexible pipeline deformation, the pipeline deformation can be divided into 12 patterns listed in Table 1, which are called deformation pattern matrix of buried flexible pipeline. Among them, Type 2 deformation pattern is related to the uncompacted backfill on the side of the pipe; Type 4 deformation pattern is the mixture of Type 2 and Type 3 patterns. Class B deformation pattern is generally related to the repair of the inner wall of the pipe, which leads to the fact that the measured pipe diameter is smaller than the factory pipe diameter; Class C deformation pattern may be related to pipeline manufacturing accuracy, which leads to the fact that the measured pipe diameter is larger than the factory pipe diameter.
Table 1. Deformation pattern matrix of buried flexible pipeline

|   | A                           | B                           | C                           |
|---|-----------------------------|-----------------------------|-----------------------------|
| 1 | **Conventional deformation pattern** | \(2b < D_0 < 2a\)       | \(2b < 2a < D_0\)       | \(D_0 < 2b < 2a\)       |
| 2 | **Great deformation of the lower half of the pipeline** | \(2b_2 < 2b_1 < D_0 < 2a\) | \(2b_2 < 2b_1 < 2a < D_0\) | \(2b_2 < 2b_1 < 2a\)       |
| 3 | **Great deformation due to lateral extrusion** | \(2a < D_0 < 2b\)       | \(2a < 2b < D_0\)       | \(D_0 < 2a < 2b\)       |
| 4 | **Great deformation of the lower half of the pipeline + great deformation due to lateral extrusion** | \(2a < D_0 < 2b_2 < 2b_1\) | \(2a < 2b_2 < 2b_1 < D_0\) | \(2a < 2b_2 < 2b_1\)       |

2.3 Verification method of pipeline deformation pattern test results

In order to verify the relationship between the deformation pattern of the pipeline and the compactness of backfill on the side of pipeline, the elastic waves measuring method was adopted for verification, as shown in Figure 2. The measured impact response strength is a relative index, and the research demonstrated that [7] the closer the defect is to the striking point, the larger the defect area and the greater the impact response strength are; the farther the defect is from the striking point, the longer the delay time for the impact response signal to reach the detector is. Therefore, the size and location of defects could be estimated qualitatively according to the delay time for the impact response signal to reach the detector and the signal strength. In this study, the impact response signals collected from each measuring point on the inner wall of the same pipe section were statistically analyzed, and the maximum and average values of the impact response strength of each pipe section were calculated, which were taken as a measurement of the compactness of the backfill outside the whole pipeline. The greater impact response strength indicated that the compactness of backfill on the side of the pipe was worse.

![Figure 2. Test method for compactness of backfill on the side of the pipe](image-url)

In order to understand the actual performance of pipes after many years of operation, the intact
pipes dismantled recently in the project were sampled and tested. Sampling and testing were entrusted to a qualified testing center, and the testing and analysis were carried out according to relevant specifications [8]. Among them, indicators such as the bending strength and hoop tensile strength of pipe wall were important bases for structural safety assessment.

3. Safety assessment method of buried flexible pipeline structure

Spangler’s formula for deformation of flexible pipeline structure is as follows:

\[ w_d = D_L \frac{k_d f_0^2 (W)}{E_p I_p + 0.061 E_s r_0^2} = D_L \frac{k_d (W)}{8 s_R + 0.061 E_s^2} \]  

(6)

Where, \( w_d \) is the vertical deformation of the pipeline; \( D_L \) is the coefficient of deformation hysteresis, which is generally 1.2–1.5; \( k_d \) is the deformation coefficient of the pipeline. In accordance with the angle \( 2 \alpha \) of the support portion at the bottom of the pipeline, when \( \alpha = 60^\circ \), there is \( k_d = 0.089 \), and when \( \alpha = 0^\circ \), there is \( k_d = 0.110 \); \( r_0 \) is the calculated radius of the pipeline; \( W \) is the soil load; \( E_p \) is the elastic modulus of pipe, and \( I_p \) is the moment of inertia of pipe wall section; \( E_s \) is the stiffness of soil beside the pipe; \( S_R \) is the ring-bending stiffness of pipeline.

Theoretically, for the pipeline under Type 1 conventional deformation pattern, the internal force of the pipe wall can be calculated according to Spangler’s formula. The values of the coefficient of deformation hysteresis \( D_L \), the deformation coefficient of the pipeline \( k_d \), and the stiffness of soil on the side of the pipe \( E_s \), mainly depend on the experience, and the accuracy is not high. For Type 2, Type 3 and Type 4 deformation patterns, Spangler hypothesis is not valid, so Spangler’s formula cannot be used for calculation.

The internal force and reliability index of pipeline structure were calculated according to the back analysis of the measured deformation results. The elliptic curve equation and the factory section were compared, and the vertical displacement \( \Delta y \) and horizontal displacement \( \Delta H \) of each point on the pipe wall were calculated. The method of finite element analysis was adopted, modeling was only made for the pipeline structure, and the vertical displacement \( \Delta y \) and horizontal displacement \( \Delta H \) of each point were applied to the pipe wall as forced displacement, so that the internal force distribution on the pipe wall section in the emptying state could be obtained. At this time, the reaction force on the displacement boundary of the pipe wall was the earth pressure. Furthermore, according to the superposition principle, the internal force of pipe wall under the combined action of water body weight, water pressure and earth pressure outside the pipe could be calculated. And then, the safety assessment of pipeline structure could be carried out according to the results of pipe sampling and testing.

4. Engineering cases

4.1 Engineering situation

A diversion project in SZ, a coastal area in southern China, was taken as an example. The project was completed in May 2010, and various pipes were used to transport raw water, among which the fixed-length FRPM section with a pipe diameter of 2.6 m and length of 3.56 km has the buried depth of the top of pipe of 2.7 m–4 m. In addition, a large amount of stone powder was used in pipeline backfill. After 2 years’ operation, the pipeline bursts several times. The inspection results with water discharged or stopped over the years demonstrated that under the condition that the deformation of this pipeline does not exceed the standard, the pipe wall cracking is serious, and the cracks of some repaired pipe sections continue to extend. As shown in Figure 3, cracks are mainly distributed along the water flow direction, indicating that the acting forces inducing pipe wall cracking are on the same section of the pipeline, and the uneven settlement of foundation along the axial direction of the pipeline is not the main influencing factor. Therefore, the deformation inspection and analyzed were carried out for the middle section of each pipe section in the pipeline safety assessment to represent the overall working performance of the pipeline, and a total of 272 section were detected.
4.2 Detection results of pipeline deformation

The inspection results demonstrated that the radial compression deformation of the pipeline along the line did not exceed the code limit, but there were lots of pipe wall cracks and multiple pipe failures, which proved that the safety of the pipeline structure cannot be guaranteed only relying on the current code methods to control the radial deformation of the pipe top. The measured pipeline deformation is shown in Figure 4. It can be seen that the pipeline deformation pattern does not always meet Spangler hypothesis, which is the main reason for the failure of the method recommended in the code.

Spangler deformation pattern [5]  

The ratio distribution of measured vertical deformation $\Delta y$ and horizontal deformation $\Delta H$

Figure 4. Measured pipeline deformation

The above methods were adopted to classify and count the deformation patterns of pipes, and the relationship between deformation pattern and pipe wall cracking was analyzed. The results are shown in Table 2 and Table 3. According to Table 2, about 35.66% of the lower half of this pipeline is deformed greatly, indicating that the backfill on the side of the pipeline is uncompacted. It can be seen from Table 3 that about 57.7% pipe wall cracks under great deformation of the lower half of the pipeline, which is far greater than the failure rate of the pipe in other patterns. The results demonstrated that the compactness of backfill on the side of the pipe was the key factor affecting the failure rate of FRPM. It should be noted that 26.7% pipes were still damaged under the conventional deformation pattern. Since the buried depth and the internal water pressure during operation of the detected 2 km pipeline were basically the same, and there was no vehicle load interference, it indicated that the strength distribution of FRPM in this section has great dispersion.
Table 2. Classification statistical results of measured pipeline deformation patterns

|   |         | A       | B       | C       | Total   |
|---|---------|---------|---------|---------|---------|
| 1 | Conventional deformation pattern | 59.20%  | 0.37%   | 0.74%   | 60.29%  |
| 2 | Great deformation of the lower half of the pipeline | 32.72%  | 0.00%   | 2.94%   | 35.66%  |
| 3 | Great deformation due to lateral extrusion | 2.21%   | 0.00%   | 0.00%   | 2.21%   |
| 4 | Great deformation of the lower half of the pipeline + great deformation due to lateral extrusion | 1.84%   | 0.00%   | 0.00%   | 1.84%   |

Table 3. Statistical results of pipe wall cracking under various deformation patterns

|   |         | A       | B       | C       | Total   |
|---|---------|---------|---------|---------|---------|
| 1 | Conventional deformation pattern | 26.5%   | 100%    | 0.0%    | 26.7%   |
| 2 | Great deformation of the lower half of the pipeline | 61.9%   | ——      | 25.0%   | 57.7%   |
| 3 | Great deformation due to lateral extrusion | 0.0%    | ——      | ——      | 0.0%    |
| 4 | Great deformation of the lower half of the pipeline + great deformation due to lateral extrusion | 0.0%    | ——      | ——      | 0.0%    |

Note: In this table, only the sections with FRPM are counted, with statistical result = (number of broken pipe sections in this pattern)/(number of total pipe sections in this pattern), and total ratio = (number of total broken pipe sections in this pattern)/(number of total pipe sections in this pattern)

4.3 Verification of detection results of pipeline deformation pattern

Table 4 showed the statistical results of the maximum and average values of pipeline impact response strength under different deformation patterns. The maximum value and average value of impact response strength of the side wall under 2A deformation pattern are significantly higher than those under 1A deformation pattern, which indicates that the uncompacted backfill on the side of the pipe is the fundamental reason for Type 2 deformation pattern. The low compactness of backfill on the side of the pipe is related to the construction quality control. The foundation of the tested pipe section is muddy soft foundation in coastal areas, and the groundwater level is high, which is not easy to backfill and compact. In addition, steel sheet piles are widely used to support foundation pits in the construction process, and the spacing between steel sheet piles is narrow, which makes it more difficult to guarantee the backfill quality. The low compactness of backfill on the side of the pipe is also related to the hydrogeological environment. The tested section is backfilled with stone powder, which is not a real building material, has no grading control and viscosity, and has a large content of silty fine particles. The change of groundwater level will cause the change of compactness of backfill on the side of the pipe. This is also the main influencing factor that causes the continuous deformation and excessive deformation of FRPM pipeline in this project, and local stress concentration to induce
the cracking of the pipe wall.

**Table 4.** Statistical results of pipeline impact response strength under different deformation patterns

| Deformation pattern | Maximum value of impact response strength | Mean value of impact response strength |
|---------------------|------------------------------------------|----------------------------------------|
|                     | <5 | 5–10 | >10 | <5 | 5–10 |
| 1A                  | 44.23% | 50.00% | 5.77% | 90.38% | 9.62% |
| 2A                  | 21.05% | 63.16% | 15.79% | 78.95% | 21.05% |

According to the back analysis of the measured deformation results, the internal force and reliability index of pipeline structure were calculated. Table 5 showed the results of pipe sampling and testing. It demonstrated that the coefficient of variation of hoop tensile strength of pipeline reaches up to 0.21, and even the test results on the same section of pipeline have great dispersion, which strongly proves the analysis results of deformation pattern in this paper. By investigating the engineering construction files, the sampling inspection results of pipes were compared and shown in Table 6. It indicated that the axial tensile strength of the pipeline decreased significantly, and the mean value of hoop tensile strength changed slightly, while the coefficient of variation increased greatly.

**Table 5.** Results of pipe sampling and testing

| Pipe wall thicknesses (mm) | Ring-bending stiffness (N/m) | Hoop tensile strength (kN/m) | Axial tensile strength (kN/m) | Ring-bending strength (MPa) |
|---------------------------|------------------------------|------------------------------|-----------------------------|---------------------------|
| Average value             | 44.63                        | 8890.7                       | 5588.1                      | 358.5                     | 206.0                     |
| Standard deviation        | 1.30                         | 510.2                        | 1164.6                      | 31.5                      | 14.5                      |
| Coefficient of variation  | 0.03                         | 0.06                         | 0.21                        | 0.09                      | 0.07                      |

**Table 6.** Factory inspection results of pipes

| Pipe wall thicknesses (mm) | Ring-bending stiffness (N/m) | Hoop tensile strength (kN/m) | Axial tensile strength (kN/m) | Ring-bending strength (MPa) |
|---------------------------|------------------------------|------------------------------|-----------------------------|---------------------------|
| Average value             | 45.66                        | 8647.7                       | 5549.5                      | 648.5                     | N/A                       |
| Standard deviation        | 0.60                         | 380.1                        | 311.0                       | 70.7                      | N/A                       |
| Coefficient of variation  | 0.01                         | 0.04                         | 0.06                        | 0.11                      | N/A                       |

For the structure of fixed-length FRPM, the axial tensile strength mainly reflects the mechanical properties of resin matrix in the pipe wall, while the hoop tensile strength comprehensively reflects the combined action of fiber and resin matrix. It can be seen that, compared with the factory inspection results, the strength of the resin matrix in the pipe wall is greatly attenuated, which also leads to the decrease of the adhesive properties of the fiber and the resin matrix and the significant increase of the coefficient of variation of the hoop tensile strength.

**4.4 Safety assessment results of pipeline structure**

According to the deformation inspection results, the average hoop tensile stress and bending stress under the comprehensive action of inner water pressure and earth pressure in the design as well as the maximum hoop tensile stress of the inner wall of the pipeline were calculated section by section. Due to the large dispersion of pipe strength, the reliability indexes $\beta_1$, $\beta_2$ and $\beta_3$ corresponding to bending failure, hoop tensile failure and pipe wall cracking of pipeline structure were calculated according to the results of pipe sampling and testing.
According to the structural reliability theory [9] and relevant standards [10], the reliability index method was adopted to conduct the safety assessment of pipeline structure and safety classification, and five levels of pipeline structure safety were classified, as shown in Table 7.

**Table 7. Classification of safety level of pipeline structure**

| Pipeline safety level | Reliability index | Remarks                              |
|-----------------------|-------------------|--------------------------------------|
|                       | Bending failure   | Hoop tensile | Pipe wall cracking | Remarks                              |
| Level I               | $\beta_1 \geq 4.2$ | $\beta_2 \geq 4.2$ | $\beta_3 \geq 3.2$ | The pipeline is in good condition     |
| Level II              | $3.7 \leq \beta_1 < 4.2$ | $3.7 \leq \beta_2 < 4.2$ | $\beta_3 \geq 3.2$ | The pipeline is deformed greatly and there is no risk of cracking |
| Level III             | $\beta_1 \geq 4.2$ | $\beta_2 \geq 4.2$ | $\beta_3 < 3.2$ | The risk of pipe wall cracking is high |
| Level IV              | $3.7 \leq \beta_1 < 4.2$ | $3.7 \leq \beta_2 < 4.2$ | $\beta_3 < 3.2$ | The deformation of pipeline is large and the pipe wall cracks |
| Level V               | $\beta_1 < 3.7$ | $\beta_2 < 3.7$ |                      | The risk of pipe failure is high and the pipe needs to be replaced immediately |

According to the results of safety assessment of pipeline structure, the safety classification of this section was given, as shown in Table 8. It can be seen from the assessment results that more than 40% pipe section in this FRPM section belongs to Level IV or Level V, which is seriously damaged and needs to be replaced. In 2018, according to the conclusion of the assessment report, SZ City completely replaced the fixed-length FRPM of the diversion project.

**Table 8. Results of safety assessment of pipeline structure**

| Level  |        |        |        |        |
|--------|--------|--------|--------|--------|
|        | Level I| Level II| Level III| Level IV| Level V|
|        | 0.0% | 48.89% | 10.00% | 37.18% | 3.93% |

5. Conclusion

Combining with a diversion project, the deformation inspection and safety assessment method of large-diameter buried flexible pipeline in service was proposed in this paper. The main research results are as follows:

(1) Spangler’s formula is a theory for macroscopic evaluation of pipeline deformation, which cannot reflect the deformation state of various parts around the pipe from a microscopic view. The purpose of controlling pipeline deformation is to control the stress state of the pipeline. When the macro radial deformation of the flexible pipeline is not large, it is also possible that the local geometric size of the pipeline may change suddenly in the microscopic view due to the influence of backfill material.

(2) The real deformation state of empty pipeline could be measured by the laser scanning and piecewise elliptic curve fitting combined method. There were 12 deformation patterns of large-diameter buried flexible pipeline.

(3) The internal force of pipeline structure was calculated according to the back analysis of pipeline deformation, so that the reliability indexes corresponding to bending failure, hoop tensile failure and pipe wall cracking of pipeline structure could be obtained. Based on this, the safety assessment and safety classification of pipeline structure could be carried out accordingly.

(4) The main design point of pipe-soil interaction is to carry out pipeline landfill design instead of pipe body design according to Spangler’s formula, the stiffness and stability of pipeline should be calculated based on pipeline application scenarios (working conditions), pipeline performance (initial and long-term) and installation conditions, and these conditions should be verified in pipeline safety assessment.
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