Field Experimental Research on Application of Strain Special Optical Cable and Parallel Optical Cable

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Abstract. With the rapid development of China's oil and gas pipeline mileage, pipeline construction will be unable to avoid crossing high-risk areas such as disaster risk areas, densely populated areas, environmentally sensitive areas. The traditional extensive pipeline patrol method has been unable to meet the requirements of fine management, which puts forward a new test for the upgrade of safety monitoring technology. In this paper, the distributed optical fiber sensing technology which has been studied intensively in recent years is introduced. Through in-depth analysis of pipeline requirements and characteristics of accompanying optical cable, a single-end BOTDA solution suitable for long-distance oil and gas pipelines is proposed. A 400-meter pipeline trench was excavated along the route of a domestic product oil pipeline. Strain special cables and GYTA53 cables were laid concurrently. Twelve strain monitoring sections were set up using vibrating wire strain sensors. The strain of two kinds of optical cables was monitored under various working conditions, such as partial backfilling, full backfilling, manual compaction and heavy mechanical compaction, as well as the monitoring values of two kinds of optical cable for soil temperature. The test results show that: 1) the strain-sensitive fiber optic cable is sensitive to strain feedback, and can produce rapid feedback to 2m3 pile soil, while the stress feedback of pipeline-accompanying fiber optic cable to soil is very small. 2) The temperature around the pipeline can be accurately reflected by the fiber optic cable, and it can be used for temperature compensation in strain monitoring.

1. Introduction

As the safest, most reliable and most efficient way of oil transporting, pipeline oil and gas transportation has attracted more and more attention from all over the world. By the end of 2018, the total mileage of China's long-distance oil and gas pipeline has exceeded 130,000 kilometers, and pipeline transportation has become the main pillar of China's oil and gas transportation\textsuperscript{[1]-[3]}. However, as a linear transportation project, the pipeline has a long line and complex human and geological environment along the pipeline. The pipeline will inevitably pass through densely populated areas and geological disaster areas, facing the threat of third-party destruction and geological disasters. The traditional extensive pipeline patrol method has been unable to meet the requirements of fine management, which puts forward a new test for the upgrading of safety monitoring technology\textsuperscript{[4]-[7]}. Distributed optical fiber sensing technology is a new sensing technology, which uses sensing optical fiber as detection element and signal transmission medium. Compared with other detection
technologies, distributed optical fiber sensing technology takes optical fiber as both sensing element and signal transmission medium. It has the advantages of small size, light weight, anti-electromagnetic interference, corrosion resistance, high sensitivity, fast measurement speed, long service life and low cost, and can adapt to long-distance harsh monitoring environment. Especially in the field of safety monitoring of buried long-distance gas pipelines, the technology has natural advantages. It can realize stress hazard early warning of pipelines through distributed optical fiber strain monitoring, so that maintenance personnel can take timely preventive measures to prevent the deterioration of the situation and avoid danger. Geological subsidence caused by crustal movement, illegal exploitation, human activities and other factors results in stress and deformation of oil and gas pipelines. Sensing fiber will change the sensing stress in advance and then produce strain[8].

2. General situation of test

Over the years, PetroChina has done a lot of research work on distributed pipeline monitoring, and achieved nice results. Aiming at the third-party threat of pipeline, the technologies of optical fiber safety early warning, pipeline leakage monitoring and intelligent video surveillance in high-consequence areas are studied. Aiming at the pipeline geological hazard threat, the monitoring technology of geological hazard body, pipeline body and interaction between pipeline and soil is studied. However, with the development of China's urbanization and the change of global geological environment, the human geological environment along the pipeline has become more and more complex. It is not practical to requisition land and lay special optical cables on all existing pipelines. Whether the existing pipeline accompanying optical cables can meet this heavy task needs further research. China Petroleum Pipeline Research and Development Center has carried out a series of field tests to solve this problem. A product pipeline under the jurisdiction of China Petroleum Pipeline Company was selected to expropriate 400 meters of land along the pipeline. Special strain cables and GYTA53 cables were laid concurrently. 12 strain monitoring sections were set up with vibrating string strain sensors, and partial backfilling, all backfilling, manual compaction and heavy machinery were monitored throughout the process. The strain magnitude of the two kinds of optical cables under various conditions such as compaction, and the monitoring value of soil temperature with the change of temperature of the two kinds of optical cables. In order to ensure that the optical cable is not broken, the 400-meter trench is excavated by hand with 30 manpower input for 5 days. During the excavation period, more land-occupying problems are involved. The final project is completed in 10 days. Fig. 1 is the process map of the field excavation, and Figure 2 is the map after the laying of the optical cable.

3. Principle

In 1922, Brillouin predicted Brillouin effect by calculating and analyzing light scattering with varying acoustic density. Brillouin scattering effect refers to the phenomenon of light scattering caused by the non-linear interaction between the incident light wave field and the acoustic wave field in the optical fiber. The difference between the frequency of scattered light and the frequency of incident light is called Brillouin frequency shift. Brillouin scattering can be divided into spontaneous and stimulated
Brillouin scattering according to the intensity of incident light (pump light). The instrument based on spontaneous Brillouin scattering is called Brillouin optical time domain reflector, and the instrument based on stimulated Brillouin scattering is called Brillouin optical time domain analyzer (BOTDA).

3.1. Spontaneous Brillouin Scattering
Spontaneous Brillouin scattering is an elastic-mechanical vibration caused by the spontaneous thermal motion of optical fiber particles, which makes the density of optical fiber change periodically and forms a spontaneous acoustic field. When the incident light enters the fiber, Brillouin scattering is caused by the action of the refractive index grating of the spontaneous acoustic field on the incident light. It is a scattering phenomenon under the condition of low power of incident light.

3.2. Stimulated Brillouin scattering
When the power of incident light is very high, the increase of refractive index of optical fibers produces electrostrictive effect, which makes most of the transmitted light turn into backscattered light. When the power of incident light increases, the self-released Brillouin scattering is strengthened. When the power continues to increase to a certain extent, the acoustic field generated by electrostrictive effect will stimulate more scattered light, which is called stimulated distribution Brillouin scattering (SBS). Brillouin scattering is a process of conservation of energy and momentum. Therefore, the frequency and wave vector of incident light wave, scattered light wave and acoustic wave follow the following relations:

\[ \Omega_b = \omega_p - \omega_s \]  
\[ k_A = k_p - k_s \]

Among them, \( \omega_p, \omega_s \) are the frequency of incident light and Stokes light. \( k_p, k_s \) are the wave vectors incident light and Stokes light. Acoustic frequency \( \Omega_b \) and wave vector \( k_A \) satisfy the following dispersion relation:

\[ \Omega_b = V_A |k_A| \approx 2V_A |k_p| \sin\left(\frac{\theta}{2}\right) \]

Among them, \( V_A \) is acoustic frequency and \( \theta \) is the scattering angles of incident and Stokes waves. The scattering of light in single mode optical fibers is only forward and backward. Brillouin scattering only occurs backward. When the scattering angle is 180 degrees, Brillouin frequency shift is the largest, as shown in the formula:

\[ v_B = \frac{\Omega_b}{2\pi} = 2nV_A / \lambda_p \]  
\[ V_A = \sqrt{\frac{(1-\mu)E}{(1+\mu)(1-2\mu)\rho}} \]

Formula (4) and (5) show that the Brillouin frequency shift is related to the sound velocity \( V_A \) in the fiber and the wavelength \( \lambda_p \), refractive index \( n \), elastic modulus \( E \), Poisson's ratio \( \mu \) and density \( \rho \) of the incident light. The external temperature and strain change the refractive index \( n \) of the optical fiber through the thermo-optic effect and elasto-optic effect of the optical fiber. At the same time, the temperature and strain change can change the sound speed of the optical fiber \( V_A \) by
adjusting the elastic modulus $E$, Poisson's ratio and density of the optical fiber. Therefore, the measurement of temperature and strain of the measured structure can be realized by measuring the Brillouin frequency offset.

(3) The Relation between Light and Temperature and Strain

The optical fiber sensor is compact in structure, light in weight, and has no current passing through the detection position, so it is not subject to electromagnetic interference. A large number of experimental studies and engineering practices have proved that optical fiber sensors can survive in harsh service environment.

In 1995, the scholar Horiguchi found that Brillouin frequency has a linear relationship with temperature and strain changes and meets the following relationships:

$$\nu_b(T, \varepsilon) = C_\varepsilon (\varepsilon - \varepsilon_0) + C_T (T - T_0)$$

Among them, $C_\varepsilon$ and $C_T$ represent Brillouin strain coefficient and Brillouin temperature coefficient respectively. $\varepsilon$ is measured strain, and $T$ is measured temperature. $\varepsilon_0$ and $T_0$ correspond to the reference initial strain and the reference initial temperature of Brillouin frequency shift in the initial state, respectively[9]-[10].

4. Experiments

In the field test, the equipment of Omnisens company in Switzerland was selected and the special strain optical cable of a Swiss company was laid.

4.1. Working Principle of Instrument

In this paper, the distributed strain temperature monitoring system of BOTDA + BOTDR of Omnisens Company in Switzerland is used. Based on the principle of stimulated Brillouin scattering, pump and CW probe are injected into both ends of the optical fiber. When the frequency difference between pump and probe is equal to Brillouin frequency shift, stimulated Brillouin scattering is generated. Because of the double-end injection, loop measurement is adopted. While connecting the sensing fiber, it is necessary to connect the loop fiber to form a loop. The technical specifications of the equipment are as follows:

| Classification  | Index                        | BOTDR+BOTDA          |
|-----------------|------------------------------|----------------------|
| Measuring Distance | 60km (120km max)             |                      |
| Numbers of Channels | 4                           |                      |
| Sensing Optical Fiber | ITU G.652,657,655             |                      |
| Spatial Resolution | 0.5-20m                      |                      |
| Measurement Resolution | 0.1°C/2με                    |                      |
| Measuring Quantities | Temperature, Strain and Brillouin Frequency Shift | |
| Communication interface | RJ45                        |                      |
| Size             | 449×500×178                  |                      |
| Weight           | 15kg                         |                      |
| Water-proof Grade | IP20                         |                      |

4.2. Optical cable used in the test

The strain special optical cable used in the test is made in Switzerland. It consists of HDPE sheath, steel strand, steel wire sleeve and coated optical fiber, as shown in Figure 3.
Fig3. Structure of Special Optical Cable

In order to compare the difference of strain and temperature sensing characteristics between special optical cables and communication cables, special optical cables and communication cables are laid on one side of the pipeline in parallel, and welded at one end of the pipeline, while the other side acts as the measuring end.

Fig4. GYTA cable structure

Fig5. Layout of pipeline and cable

4.3. Overview of field installation

In Shandong Province, China, a product pipeline route is excavated with a length of about 400 meters from the trench to the bottom of the pipeline. The outer diameter of the pipeline is 316.5 mm, the wall thickness is 5 mm, and the operating pressure is 4-6 MPa. Plane layout and cable installation drawings are shown in Fig. 6.

Fig6. Layout of optical cable installation

4.4. Experimental data analysis

(1) Initial state
Figure 8 shows that due to the different Brillouin center frequencies of the two optical cables, it can be clearly distinguished. According to the site construction requirements, soil bags will be installed every 12 meters (Fig. 7), so it can be seen from Fig. 8 that both optical cables have a small sharp edge. For strain monitoring optical cables, the change of compression part (small peak) is about 15.7MHz for communication optical cables, and the change of compression part (small peak) is about 4.5MHz for communication optical cables. The change of strain can also be reflected under direct compression. But compared with strain monitoring optical cables, the change is very small, about 28.66% for strain monitoring optical cables.

(2) Sand burial along the whole line
After burying sand in the whole line, as shown in Figure 9, the difference between the two kinds of optical cables is very obvious (Fig.10). There is almost no obvious change in the whole line of communication optical cables. For strain monitoring optical cables, the maximum change is about 48.49MHz. For communication optical cables, the maximum change is about 6.87MHz. Compared with strain monitoring optical cables, the variation of communication optical cables in burying sand is quite small.

(3) Mechanical backfill
As can be seen from the table2 and the measurement results in the figure11, figure 12 below, during the period of large backfilling, the communication optical cable has little perception of the soil changes during backfilling compared with the strain monitoring optical cable. Therefore, the communication optical cable can not accurately reflect the changes brought about by the changes in geological conditions.
Table 2. Strain Cable and Communication Cable Data in Backfilling Process.

| Process          | Strain Cable Monitoring | Communication optical cable |
|------------------|-------------------------|-----------------------------|
| First measurement| 16.39 MHz               | 1.42 MHz                    |
| Second measurement| 16.62 MHz              | 0.86 MHz                    |
| Third measurement | 16.52 MHz              | 2.48 MHz                    |
| Fourth measurement| 25.23 MHz              | 0.75 MHz                    |
| Fifth measurement | 22.4 MHz               | 2.37 MHz                    |
| Average value    | 19.432 MHz             | 1.576 MHz                   |

Fig13. Whole backfilling process to temperature diagram

From the results of each measurement in the table above, it can be seen that during the period of large backfilling, the communication optical cable has little perception of soil changes during backfilling compared with strain monitoring optical cable. Therefore, the communication optical cable can not accurately reflect the changes brought about by changes in geological conditions.

5. Conclusion

Through field tests, the following conclusions can be drawn:

(1) Strain-specific optical cables are sensitive to strain feedback, which can provide rapid feedback to 2m3 pile of soil, while pipeline-accompanied optical cables have minimal feedback to soil stress.

(2) The pipeline companion optical cable can accurately reflect the temperature around the pipeline, and can be used for temperature compensation of strain monitoring.
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