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A Case Study of Floating Offshore Super-Long Steel Pipeline Combing with Field Monitoring

Jin Yu [1,*], Chonghong Ren [1], Yanyan Cai [1], Jian Chen [1], Yuanqing Wang [2] and Weiyun Chen [3]

[1] Fujian Research Center for Tunneling and Urban Underground Space Engineering, College of Civil Engineering, Huaqiao University, Xiamen 361021, China; chren173@163.com (C.R.); yycai@hqu.edu.cn (Y.C.); CJ12011201@163.com (J.C.)
[2] Xiamen Water Group Co. Ltd., Xiamen 361008, China; 13806084166@139.com
[3] Institute of Geotechnical Engineering, College of Civil Engineering, Nanjing Tech University, Nanjing 210009, China; cwy@njtech.edu.cn
* Correspondence: bugyu0717@163.com

Abstract: How to control deformation and avoid resonance is the key to ensuring the safety of the super-long pipeline when it is floating in the sea. Based on the deformation warning value of pipeline prototype composite material obtained from laboratory tests, the raw water pipeline project in Tong'an Xiamen adopts wireless communication equipment to transmit data, supplemented by aerial photography technology to monitor and feedback the strain and vibration during the dynamic construction of long-distance pipeline floating transportation. Combined with dynamic construction, this monitoring method avoids excessive deformation and resonance of the steel pipeline during floating transportation, and prevents the destruction of the anticorrosive coating. The airtightness test after completion shows that the whole pipeline meets the acceptance requirements. The monitoring results show that the strain at the bent position of the pipeline is large in the process of floating transportation, and the jacking speed and position of the tugboats have an important influence on the deformation of the pipeline. The same type of project should focus on these aspects and timely feedback monitoring data. At the same time, the study also provides detailed strain, modal analysis and effective monitoring technology for the safety of offshore steel pipeline floating transportation.

Keywords: marine floating transport; field monitoring; dynamic construction; steel pipeline strain; vibration mode

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1. Introduction

The construction of the trans-sea pipeline is an important part of the municipal pipeline project. Due to the complexity of the sea environment, the construction of the pipeline floating on the sea is difficult. The existing floating transportation method is mostly a single pipeline segment floating by segment, while the overall floating transportation technology of super-long pipeline is to float the whole pipeline to the sinking position after individual pipelines make up the whole. Ye et al. [1] studied the mechanical properties of the whole sinking process of super long asymmetric pipe. Compared with the pipe-laying vessel method [2] and pipeline jacking method [3], this construction method has less navigation influence, shorter construction period, less influence from geological conditions and low construction cost, it can complete the laying of underwater long-distance water conveyance pipeline with high efficiency and high quality. However, floating transportation on the sea is greatly affected by wind, wave and flow, so real-time monitoring feedback and dynamic adjustment are the keys to ensuring the safety of floating transportation of steel pipelines.

The Marine environment is complex. There are three main methods to study ocean engineering: theoretical research [4–6], numerical simulation [7–9], indoor modal and on-site test [10–13]. Compared with other methods, field monitoring can obtain the raw data of Marine structures and track the effective information in real-time, which provides essential support for offshore installations and reduce the risk of accidents [14,15]. At present, the monitoring methods of offshore pipelines mainly include fiber Bragg grating, acoustic emission and wireless sensor testing. Brower et al. [16] used optical fiber to monitor submarine pipelines as early as 2004. Ren et al. [17] apply Distributed Optical Fiber Sensor (DOFS), including strain and temperature sensors, to the health monitoring of the Bohai CB271 oil production platform. The experimental investigations on a method for distributed detection of lateral buckling in subsea pipelines with Brillouin fiber optic sensor were conducted by Feng et al. [18]. Xu et al. [19] developed a new Fiber Bragg Grating (FBG)-based bundle-structure riser stress monitoring sensor which could meet the requirements of riser safety monitoring in offshore oil fields. Fiber Bragg gratings are easy to move and paste, and the installation process has less impact on the pipeline surface. However, it also has some disadvantages, such as chirps and creeps. Jin and Eydgahi [20] proposed monitoring of distributed pipeline systems by acoustic sensor networks. Based on the Underwater Acoustic Sensor Networks, Wang et al. [21] proposed an energy-efficient data transmission scheme called EGRC (Energy-efficiency Grid Routing based on 3D Cubes). Mahmutoglu and Turk [22] proposed a novel passive acoustic-based system that could locate the leak holes and determine their size remotely. The acoustic sensor is portable and easy to install, but it is sensitive to environmental noise and prone to false positives. The Independent Remote Monitoring System (IRMS) of Mexico deepwater floating is fully independent of the primary Integrated Marine Monitoring Systems (IMMS) system in terms of sensors [23]. An energy-efficient cooperative scheme for wireless sensor network (WSN) nodes used in long-distance water pipeline monitoring systems was proposed by Seddiq et al. [24]. Huang and Nagarajaiah [25] developed new structural health monitoring (SHM) techniques, in which, the degree of damage was determined by local monitoring using a robotic crawler with magnetic flux leakage (MFL) sensor. It could monitor damage due to vibration fatigue. Production Systems Unmanned aerial vehicles (UAVs) technology prototypes to monitor pipelines were introduced by Gómez and Green [26]. The unmanned aerial vehicles technology is suitable for the overall monitoring of long and large pipelines, but it is not mature yet. Furthermore, besides the monitoring method, the mechanical and deformation characteristics of the pipeline body are also worthy to attend. Many efforts focused on the material characteristics and deformation mechanism of the pipe body. Wang Y et al. [27] investigate the transverse impact response for ultra-lightweight cement composite (ULCC) filled pipe-in-pipe structures through a parametric study using both a validated finite element procedure and a validated theoretical model. ESPÍN-LAGOS et al. [28] have determined through mechanical tests, metallographic analysis, and morphological studies that the degree of discoloration of the HAZ is directly affected by the atmospheric oxygen content during purging, and it has been proven to have a good electrical resistance in welded joints. Kiss I et al. [29] measured the characteristics of stainless steel during large plastic deformation through a hot torsion test, and obtained the best heating temperature range for the studied steel deformation.

Offshore pipeline monitoring is a challenging task. The main concerns are pipeline stress and strain, pipeline leakage and vibration. Relevant scholars have conducted a large number of studies on the offshore pipeline. They focused on a single fixed pipeline joint and ignored the deformation of the pipeline itself. For ultra-long pipelines, there will inevitably be an error in the calculation of force exerted on them by these methods. Guo et al. [30] analyzed stress states of pipelines upon floating by using the Finite Element Calculation method. Chen et al. [31] presented a probabilistic methodology for monitoring the condition of offshore pipelines and predicting the reliability considering stress observation and structural deterioration. There were many ways to monitor pipeline corrosion and leakage. Arumugamr et al. [32] described the application of the finite element method (FEM) and the development of equations to predict the failure pressure of single corrosion affected pipelines subjected to internal pressure and axial compressive stress. Aniskin A et al. [33] introduced the application of the boundary element method in the calculation of a closed cylindrical shell of stepped thickness, and compared it with two numerical methods: boundary and finite element. Negative pressure wave [34] and dynamic modelling [35,36] methods were used to monitor pipeline leaks. Almazyad et al. [37] presented a scalable design and simulation of a water pipeline leakage monitoring system using Radio Frequency Identification and Wireless Sensor Network technology. The study on the vibration of the pipeline is mostly about the vibration characteristics of the submarine pipeline during the period of use, while the study on the vibration of the floating pipeline is less. Jin and Shao [38] presented numerical simulations and experimental verification of a vibration-based damage detection technique. Goldsmith et al. [39] suggested that fatigue could be calculated based on the modal shape of response and amplitudes from the monitoring data. Yang et al. [40] investigated the transverse vortex-induced vibrations (VIVs) of a submarine pipeline near an erodible sandy seabed under the influence of ocean currents by a series of experiments. Considering the function of inertia and dampness, under the optimal span, a frequency response analysis was carried out. Zhang et al. [41] proved that resonance did not happen between the pipeline and wave. One marine riser fatigue acoustic telemetry scheme was proposed by Li et al. [42] to monitor deep and ultra-deepwater risers' vibration fatigue. Sollund et al. [43] studied the dynamic response of multiple ocean pipelines. A semi-analytical method for the multi-spans offshore pipeline was developed by them, which provided a fast and accurate alternative to finite element modeling of potentially interacting spans. Also, Cook et al. [44] proposed 'Threshold' monitoring by comparing measured data at alert levels to determine whether key performance indicators have reached a critical or near-critical level.

There is a lack of on-site data for the super-long steel pipeline floating project, and it is also difficult. Determination of deformation warning value of steel pipeline and 3PE composite material, monitoring instrument accuracy, waterproofing and long-distance signal attenuation, the monitoring scheme and the dynamic construction method which can effectively reduce the deformation and resonance of the pipeline, these are problems urgent to solve and design. Based on the project in Tongan Xiamen, this paper attempted to carry out on-site monitoring and real-time feedback of long-distance offshore steel pipeline floating transportation, and studies the monitoring scheme, dynamic construction method and deformation characteristics of offshore pipe floating transportation.

2. Project Characteristics

2.1. Project Profiles

Raw water pipeline project locates in Tongan Xiamen (Pile No. C2 + 187.77~C3 + 565.91). The length of pipeline 1 is 595 m in the straight pipeline and 120m in the oblique pipeline section, totally 715 m; the length of pipeline 2 is 370 m in the straight pipeline section and 290 m in the oblique pipeline, totally 660 m. The whole pipeline is 1375 m long, 1600 mm in diameter, about 1087 t in weight, 20 mm in the wall thickness, and coated with 3PE anticorrosive coating on the surface. The whole pipeline is similar to the inverted rainbow pipeline structure. Both of the two pipelines are relatively long, so it is difficult to arrange the position of tugboats and towing force during floating transportation. The reasonable arrangement of tugboats can make the pipelines bear even force in the floating transportation process and avoid the local deformation of the pipelines. The floating pipeline section operates in a cross-flow direction from the downstream direction, with a turning angle of about 90°, and the detailed floating routes of the two pipelines are illustrated in Figure 1. The vertical distance of the floating pipeline is 800 m and the route is 1.15 km. Due to the influence of sea surface width and the Tong'an bridge, it is difficult to float the whole pipeline at a time. Therefore, the pipeline 1 was floated to the sinking position firstly, then the pipeline 2 was floated, the two pipelines were welded at the sinking position in the sea. Finally, the whole pipeline was sunk at once. The floating transportation process is shown in Figure 2.

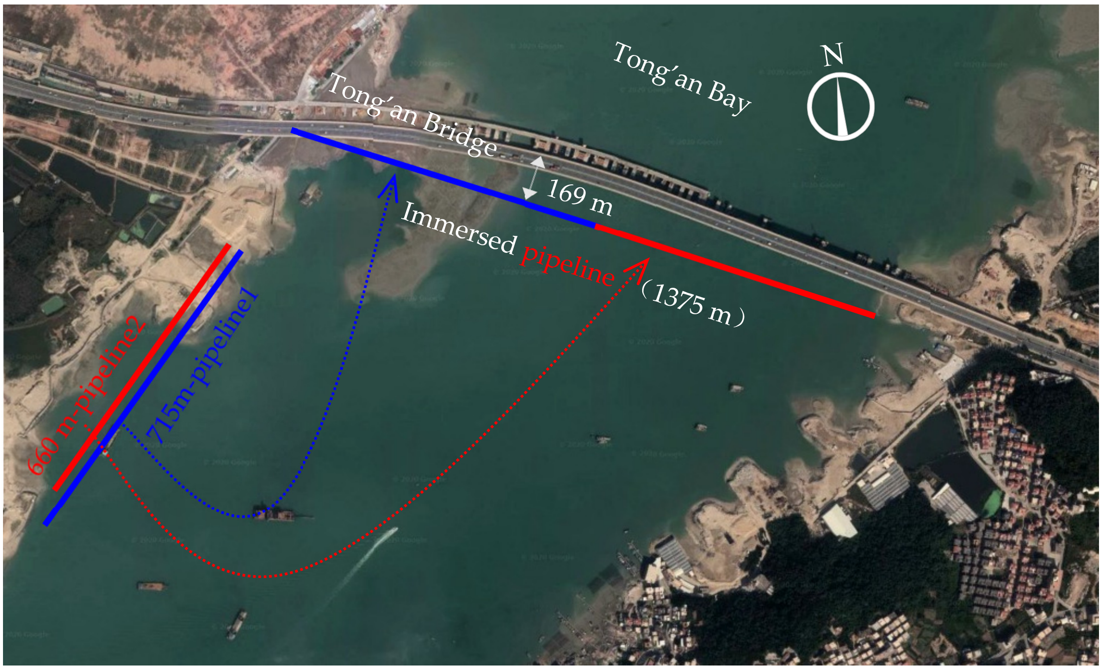

Figure 1. Satellite image of immersed pipeline segment (taken from Google map).

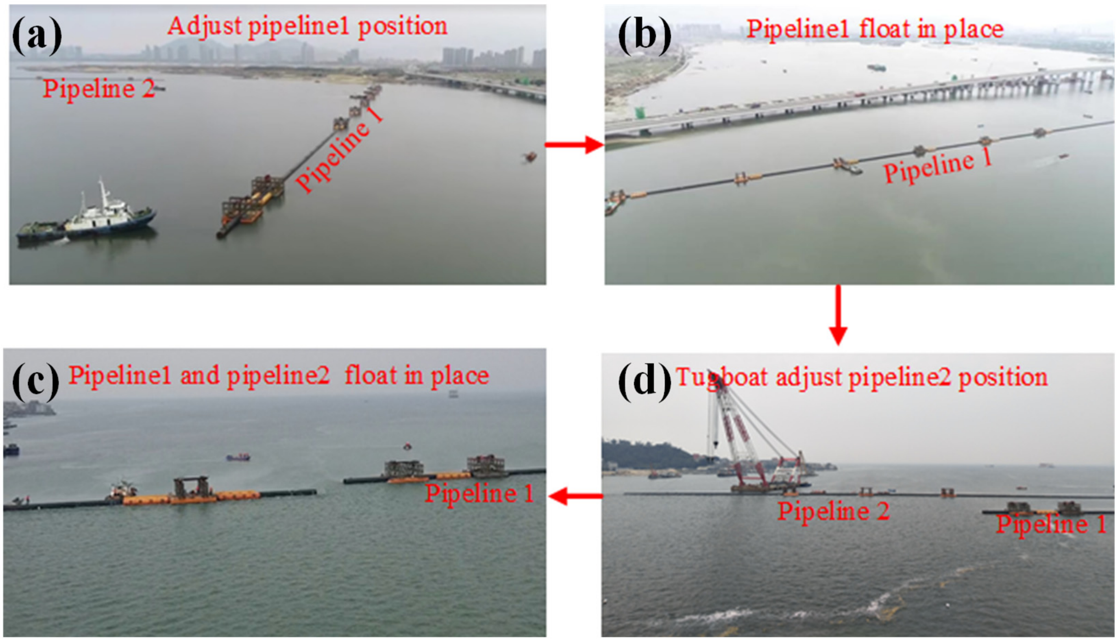

Figure 2. Aerial photo of floating transportation on site.

2.2. *Key Engineering Problems*

2.2.1. The Particularity of Offshore Construction

Offshore construction tools and monitoring have certain particularities. The wind, wave and flow on the sea are unpredictable and non-artificial. The change of weather has a great impact on the construction environment on the sea, and the change of the flow at the estuary is more drastic. Long and large pipelines are susceptible to wind, wave and flow during floating transportation. If the pipeline body deforms too much under the action of external forces, the damage is irreversible, and the pipeline quality and later service will have very adverse consequences. If the raw water pipeline is damaged, it is difficult to repair. Akram A et al. [45] providing insights on the use of thermosetting liner for the repair of offshore pipelines exposed to corrosion and leakage. The seawater erodes the pipeline body and pollutes the inside of the pipeline and the airtightness of the pipeline cannot meet the requirements, resulting in a huge loss of social benefits and economic benefits. The flow of liquids from the pipes into the ocean may also cause pollution and affect its sustainable development. The impact of natural elements was quantified using the ICI index (Impact Quantification Index) proposed by López et al. [46], which summarizes different sources of variation in a single value.

Secondly, offshore construction operations are not as convenient and flexible as those on land. If there is no reliable construction monitoring, operators cannot make timely and correct responses, which is likely to cause irreparable damage to engineering structures. In addition, metal objects are prone to decay after immersion in seawater, so offshore construction also requires effective waterproofing and erosion protection of precision instruments and structures.

2.2.2. The Particularity of Materials

The deformation test of steel-3PE composite material shows that the steel pipeline and 3PE would be separated from each other after large deformation. The indoor test material was the Q345 steel plate as same as the field steel pipeline material. The length, width and thickness of the steel plate were 40 cm, 20 cm and 2 cm respectively. Its surface was coated with 3PE anticorrosive and was tested on the universal material testing machine. During the testing process, the steel plate was on the top and the 3PE anticorrosive coating was on the bottom. The strain gauge was attached to the position corresponding to the steel plate and the 3PE anticorrosive coating (as shown in Figure 3), and the force was applied on the middle line of the steel plate.

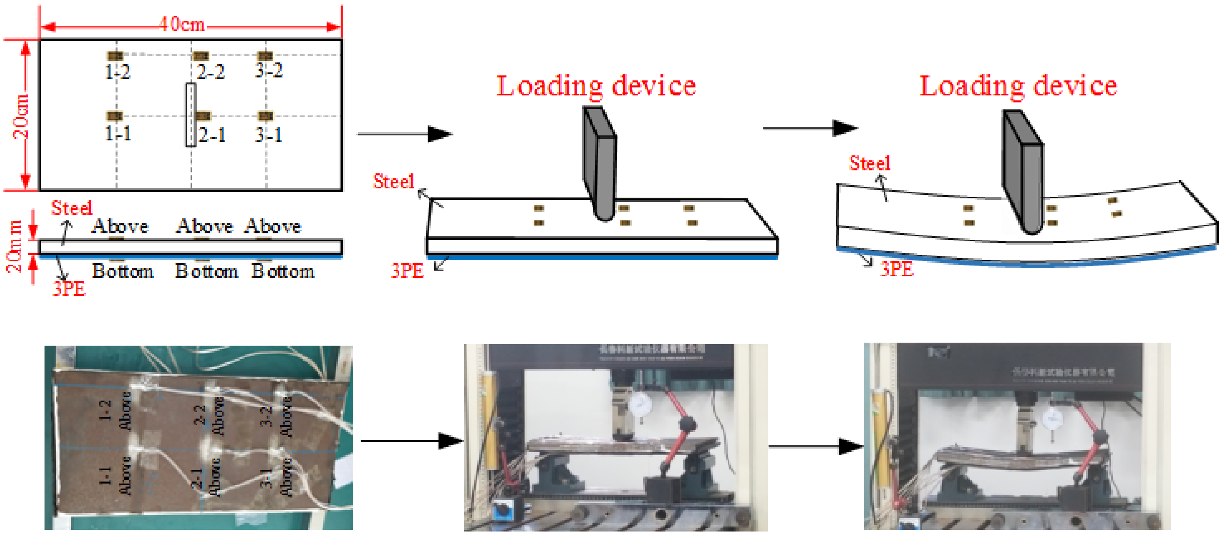

Figure 3. Laboratory test drawing of steel-3PE.

The steel-3pe deformation curve is shown in Figure 4. It can be seen that the strain at the centerline of the steel plate is the largest. When the load is about 30 kN, the center point of the steel plate (the measuring point 2-1) reaches the elastic limit state, and there is a significant difference between the steel plate and 3PE strain at the same position. The maximum strain of the corresponding steel plate is 437 $\mu\varepsilon$. If the load on the composite continues to increase, the steel plate and the 3PE material will be separated from each other. Based on the test situation and considering that the compressive strength of general welds is similar to that of the base metal, the monitoring tester suggests that the safety range of the monitoring and warning strain value could be 260 $\mu\varepsilon$. As soon as the monitoring strain approaches or reaches this value, the monitoring tester should immediately send out early warning signals and location information to the operators on the construction site.

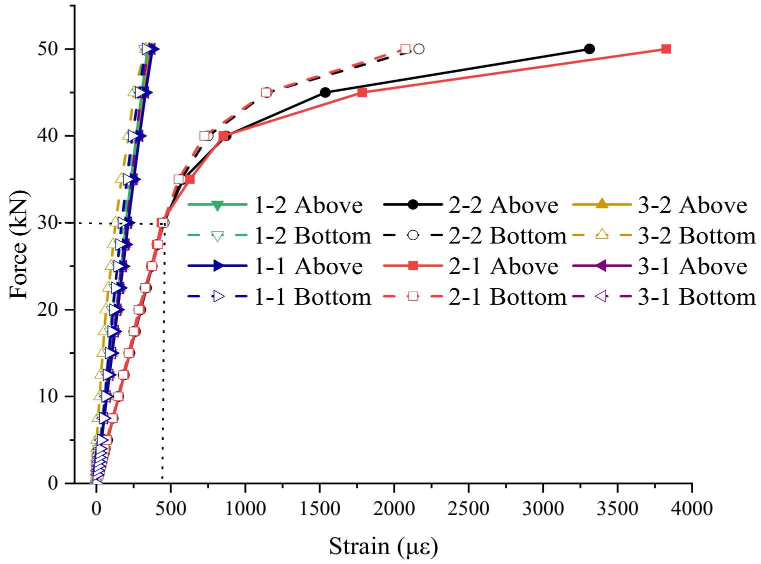

Figure 4. Deformation curve of steel-3PE.

3. Monitoring Instruments and Monitoring Programs

3.1. Monitoring Instruments

In the Marine environment, waterproofing and data transmission of monitoring equipment are the first problems to be solved. The measures adopted in this monitoring are as follows: after the strain gauge was pasted on the pipeline, it was further fixed with AB epoxy resin glue, and then sealed and coated with 703 waterproof glue, the wireless anti-interference communication system was also used to solve the problem of the interference and long-distance signal attenuation.

Figure 5 shows the specific monitoring equipment and data transmission process. The advanced isolation system of DH3819 has a strong anti-interference ability. Furthermore, it can automatically complete some functions such as the setting of parameters and the collection of data. This system has eight measurement points for each acquisition module. The maximum acquisition rate of each measurement point is 5 Hz, the obtainable strain range is $\pm$19,999 $\mu\varepsilon$, and the measurement error is less than 0.5% $\pm$ 3 $\mu\varepsilon$. The adopted communication mode is the wireless network communication; ZigBee is lightweight and portable, which can be used for wireless communication extension to reduce the field workload and improve the field test safety; DH5902N can be synchronized with GPS and can be tested and monitored in extreme environments such as strong vibration, high/low temperature and high humidity. The strain gauge was connected with the DH3819 static strain acquisition instrument through a waterproof cable-tied and fixed on the pipeline. 4 to 32 channels are provided for the system of DH3819, and all the channels can synchronously collect data, and the maximum frequency of each channel is 256 kHz. ZigBee was used to extend the wireless transmission of data. Finally, the data was transmitted to the computer through USB. The acceleration sensor was connected with the DH5902N mode acquisition instrument via a waterproof cable, and the computer received data through WiFi. The floating transportation dynamic construction could be completed through real-time monitoring and data analysis and the real-time feedback of aerial photography technology.

A lifting test was carried out before floating to ensure the reliability of testing equipment and the accuracy of steel pipe monitoring data. The test method is shown in Figure 6. The mid-point of the steel pipeline was carried out by a hoist on-site with the spacing of the buoyancy tank was 325 m. The strain at the mid-point was monitored with the results shown in Table 1. The pipeline was regarded as a statically determined structure with two hinged ends. The theoretical strain value was calculated according to the lifting height, and compared with the measured strain value.

Figure 5. Flow chart of field monitoring data transmission.

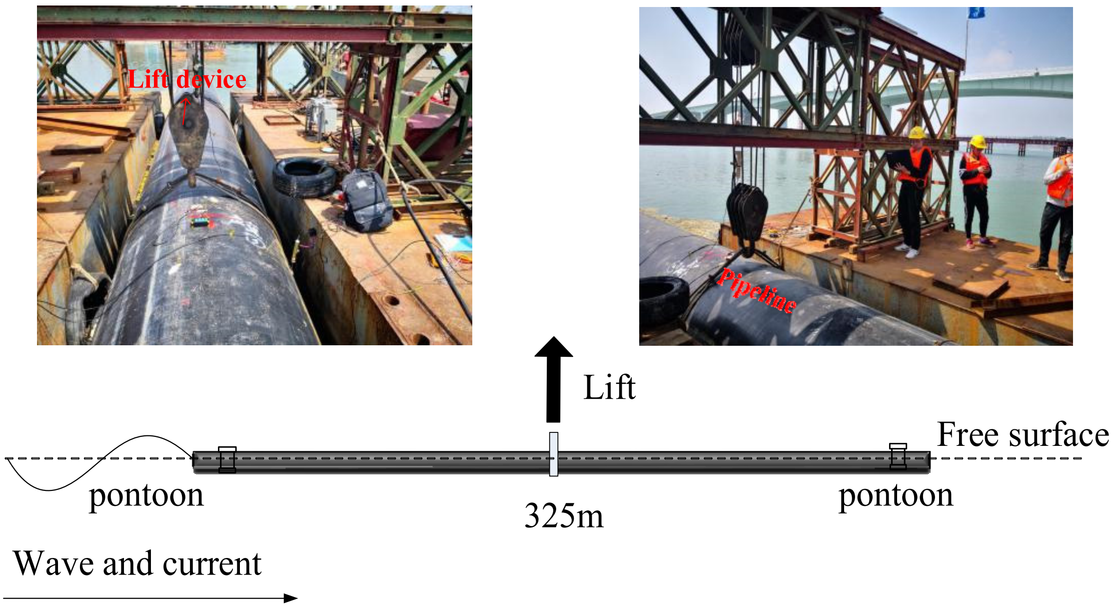

Figure 6. Lifting test on site.

Table 1. Lifting test results.

Case	Lift Height f (cm)	Theoretical Strain ε=12df/l^2 (με)	Measured Strain ε (με)	Deviation
1	7.8	14.18	14.76	4.09%
2	9.5	17.27	17.8	3.07%
3	11.2	20.35	18.91	7.08%
4	12.9	23.45	21.55	8.10%
5	14.6	26.54	24.66	7.08%

3.2. Monitoring Programs

3.2.1. Arranging the Number of Tugboats

The water flow force on the steel pipeline was estimated to determine whether the number of floating tugboats was sufficient. The calculation method of water flow force was referred to in the literature of Chen and Ren [47], and the calculation formula of the maximum water flow force of the pipeline Section 1 is as follows:

$$F_D = 1/2 C_D \rho u^2 S \tag{1}$$

where: F_D is water flow force, N; C_D is the drag coefficient, which is 1.2; ρ is the density of water, which is 1000 kg/m^3 according to the test data. u is the water flow velocity, and 0.35 m/s is taken according to the test data. S is the area facing the flow (the submergence depth is 0.4 D, D is the diameter, m), m^2.

It is generally believed that 1 KW = 1.36 horsepower, and the drag force per 1 KW is 199.92 N. Therefore, one 700-horsepower tugboat and three 120-horsepower tugboats were equipped in the floating transport process of pipeline Section 1, and the maximum towing force was 155,812.2 n > 33,633.6 n, which met the requirements of floating transport towing force.

During site construction, the tugboats should be arranged uniformly with the pontoons as far as possible, and rotated from the downstream to the transverse direction with a larger radius of curvature. Under the condition of overcoming buoyancy resistance, the tugboats kept the same power pushing on the buoyancy tank to avoid excessive deformation and 3PE destruction caused by uneven thrust. Each tugboat was equipped with a walkie-talkie and 1~2 tugboats were reserved to respond to abnormal situations timely.

3.2.2. Field Monitoring Arrangement

As shown in Figure 7 that Considering that there may be a problem of stress concentration near the bending point, strain monitors were performed near the bending section of the pipeline Sections 1 and 2 with a larger bending angle. At the same time, select a strain monitoring section near the middle of the straight pipeline section and the inclined pipeline section. Because the inclined pipeline section is longer in pipeline Section 2, two strain monitoring sections are selected here, one at the midpoint of the entire inclined pipeline, and one between the two pontoons with a larger distance. Three measuring points were arranged in each section. In the case that the water flow was perpendicular to the straight pipeline section, taking Section 1 of pipeline 1 as an example, the measuring point 1-1 belongs to the facing water, 1-2 was the top, and 1-3 was the backwater. As the bending Angle of pipeline Section 2 was only 1°, and the cable had been uncoiled to meet the construction needs before floating, the pipeline section had been flipped by 90°. Taking Section 4 as an example, the measuring point 4-1 was the top, 4-2 was the backwater, and 4-3 was at the bottom. In general, the number of measurement points had little influence on the modal parameters of natural frequency. Four modal monitoring parts were arranged in Section 2, and two measuring points were arranged on each monitoring part. Taking Section 1 as an example, measurement points 1-1 were the top and 1-2 were the backwater.

During the process of pipeline floating, the pilot boat moved synchronously with the pipeline to obtain monitoring data. The test boat of pipeline Section 1 was equipped with DH3819, which was used to receive 9 strain signals in 3 sections of the inclined pipeline section. DH3819 and DH5902N were arranged on the test boat of pipeline Section 2 to receive 12 strain signals in 4 sections of the inclined section and 8 vibration acceleration signals in 4 sections of the straight section.

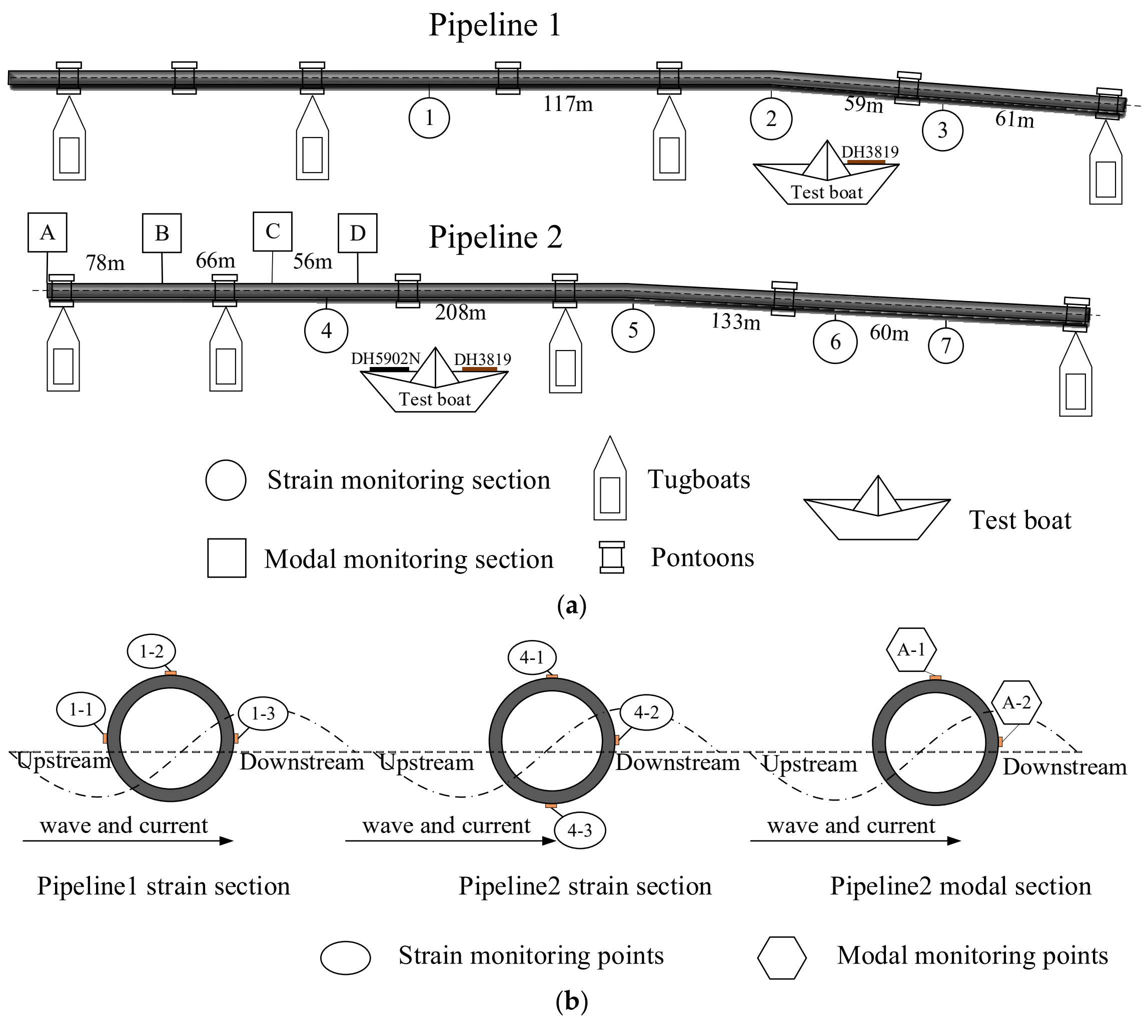

Figure 7. Arrangement of strain and modal measuring points. (**a**) Section arrangement of pipeline. (**b**) Point arrangement of section.

4. Analysis of Monitoring Results

4.1. Strain Monitoring Results

The pipeline body followed the direction of the flow before the floating movement began. After the floating movement started, the pipeline body was rotated counterclockwise at a speed of about 2°/min. It rotated to the direction perpendicular to the flow at 45 min, and to the designated position at 110 min, with the strain value tending to be stable.

Figure 8 shows the strain during the floating movement process of pipeline Section 1. The maximum tension strain at the point 1-1 facing the water surface is 99.1 με, and the maximum pressure strain is −122.3 με; at the top measuring point 1-2, the maximum tensile strain is 55.4 με, and the maximum pressure strain is −48.6 με; the maximum tensile strain is 150.9 με and the maximum pressure strain is −52.4 με at the backwater detection point 1-3. The measuring point 2-1 was located at the corner outside the surface of the water. It used a unidirectional strain gauge and the maximum strain was along the axis of the straight pipeline section. The maximum tension strain is 57.9 με, and the maximum pressure strain is −100.4 με. The measuring point 2-2 was at the top, the main stress direction is clear, and the right-angle strain flower is adopted, 0° along the axis direction and 90° vertical pipeline axis direction. The maximum tensile strain of 0° is 44.5 με, and the maximum pressure strain is −78.4 με. The maximum tensile strain of 90° is 87.7 με, and the maximum pressure strain is −60.2 με. Measuring points 2-3 at the angle of the backwater, the direction of principal stress was unknown, so the tri-directional strain flower is adopted. The maximum tensile strain of 0° is 177.9 με, and the maximum pressure strain is −99.9 με. The maximum tensile strain of 45° is 60.4 με, and the maximum pressure strain is −24.5 με. The maximum tensile strain of 90° is 44.7 με, and the maximum pressure strain is −135.7 με. The maximum tensile strain at the facing water surface measuring point 3-1 is 66.9 με, and the maximum pressure strain is −130.6 με. The maximum tension strain at the top measuring point 3-2 is 14.5 με, and the maximum pressure strain is −68.2 με. The maximum tension strain at the backwater detection point 3-3 is 85.3 με, and the maximum pressure strain is −53.1 με. The cables of measuring points 3-1 and 3-2 were pulled during floating transportation, and the strain curve shows a downward trend.

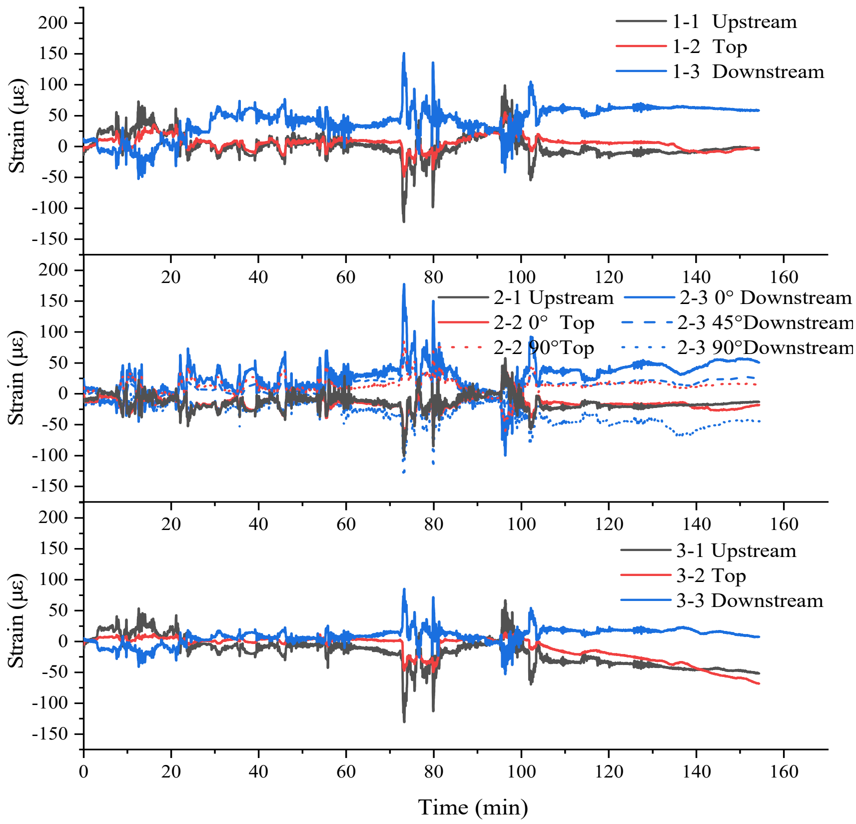

Figure 8. Pipeline Section 1 floating strain.

In the early stage of floating transport of pipeline segment 1, the pipeline rotated from downstream to cross-flow, and the middle tugboat had a large jacking force to correct it, so there was a short tension stage on the upstream and a short compression stage on the water-carrying side. At the time of floating transport of 72 min, a strong wind suddenly blew on the sea surface, causing an abrupt increase in the strain of the pipeline. In general, the strain in the floating transportation of pipeline Section 1 does not exceed the warning value. The steel pipeline is pressed against the surface of the water or pulled away from the surface of the water, and the strain curve is anti-symmetric. The strain of the windward side and the dorsal side of pipeline Section 1 is significantly greater than that of the top. The strain of the windward side and the dorsal side is the most dramatic under the influence of sea waves and flows, while the strain of the top is relatively small, and the strain of the measurement point 1 at the bend is greater than that of the measurement point 2 and 3 at the flat section.

The strain in the floating transportation of pipeline segment 2 is shown in Figure 9. The maximum tension strain at the top of measuring point 4-1 is 0.2 με, and the maximum pressure strain is −167.8 με; The maximum tension strain at the backwater detection point 4-2 is 278.4 με, and the maximum pressure strain is −151.4 με; the maximum tension strain at the measuring point 4-3 is 26.6 με, and the maximum pressure strain is 14.8 με. The maximum tension strain at the backwater detection point 5-2 is 337.8 με, and the maximum pressure strain is −123.3 με. The maximum tension strain at the top measuring point 6-1 is 29.9 με, and the maximum pressure strain is −53.6 με; the maximum tension strain at the backwater detection point 6-2 is 150.9 με, and the maximum pressure strain is -167.5 με; the measuring point 6-3 at the bottom, the maximum tensile strain is 46.0 με, and no pressure strain is observed. The maximum tension strain at the top measuring point 7-1 is 25.0 με, and the maximum pressure strain is −99.0 με; the maximum tension strain at the backwater detection point 7-2 is 89.0 με, and the maximum pressure strain is −18.6 με; the maximum tension strain at the measuring point 7-3 at the bottom is 21.4 με, and the maximum pressure strain is −5.0 με.

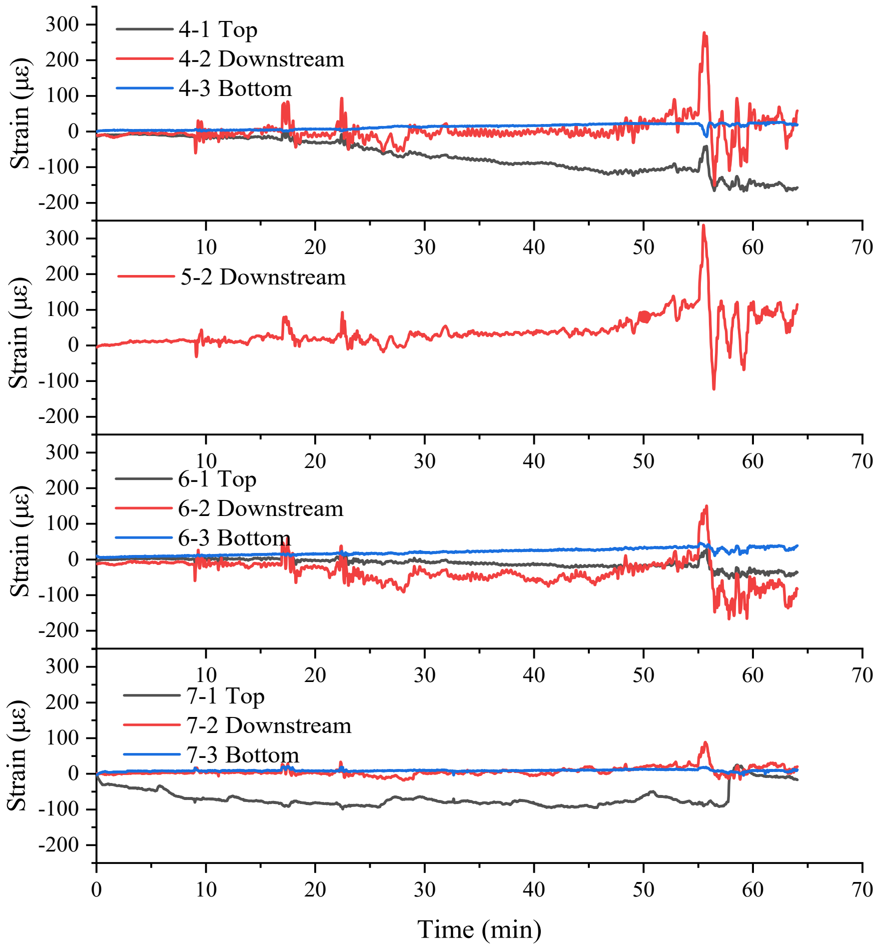

Figure 9. Pipeline Section 2 floating strain.

In the early stage of buoyancy movement of pipeline segment 2, the strain value of each measuring point is small, with the maximum strain less than 100 με. When the buoyancy movement reaches 48 min, a gale of six sprang up off the sea. In general, the strain in the floating transportation of pipeline Section 2 does not exceed the warning value. The steel pipeline is under pressure at the top, under tension at the bottom, and tension at the surface of the back. The strain change on the waterside of the pipeline is the most drastic, followed by the top and the bottom. The strain monitoring curves of test sections 4-1 show good consistency.

4.2. Dynamic Regulation

By real-time monitoring and timely warning and feedback to the construction institution, the construction institution can dynamically adjust the construction operation according to the monitoring feedback situation, avoid the pipeline damage caused by the deformation of steel pipeline and 3PE composite material, and ensure the safety of pipeline floating transportation.

At the beginning of floating transportation of pipeline Section 1, the wind speed was 3 m/s, the flow velocity was 0.35 m/s, and the wave height was 0.15 m, the axis of the pipeline was along the direction of water flow. The strain of the pipeline obtained by on-site monitoring is small and the change amplitude tends to be gentle. When floating at 72 min, a level 6 gale suddenly appears at sea, the wind speed was 6.5 m/s, the flow velocity was 0.55 m/s, and the wave height was 0.45 m. At this time, the angle between the pipeline axis and the flow direction was about 90°. The strain of the pipeline increases and the construction institution notifies the tugboats to increase the towing capacity. However, it is found that the strain suddenly increases and quickly approaches the warning value through monitoring. The monitoring personnel immediately reports the situation to the construction institution. Considering that the situation is caused by too much tugboat thrust, the operator at the construction site should be informed to reduce the tugboats thrust slowly, and always pay attention to the monitoring data, the strain data to be monitored returns to the normal level, that is, stop reducing the thrust of the tugboats. As shown in Figure 10, real-time monitoring and construction cooperate to dynamically adjust the construction operation (Section 2 at the bend is the maximum main strain).

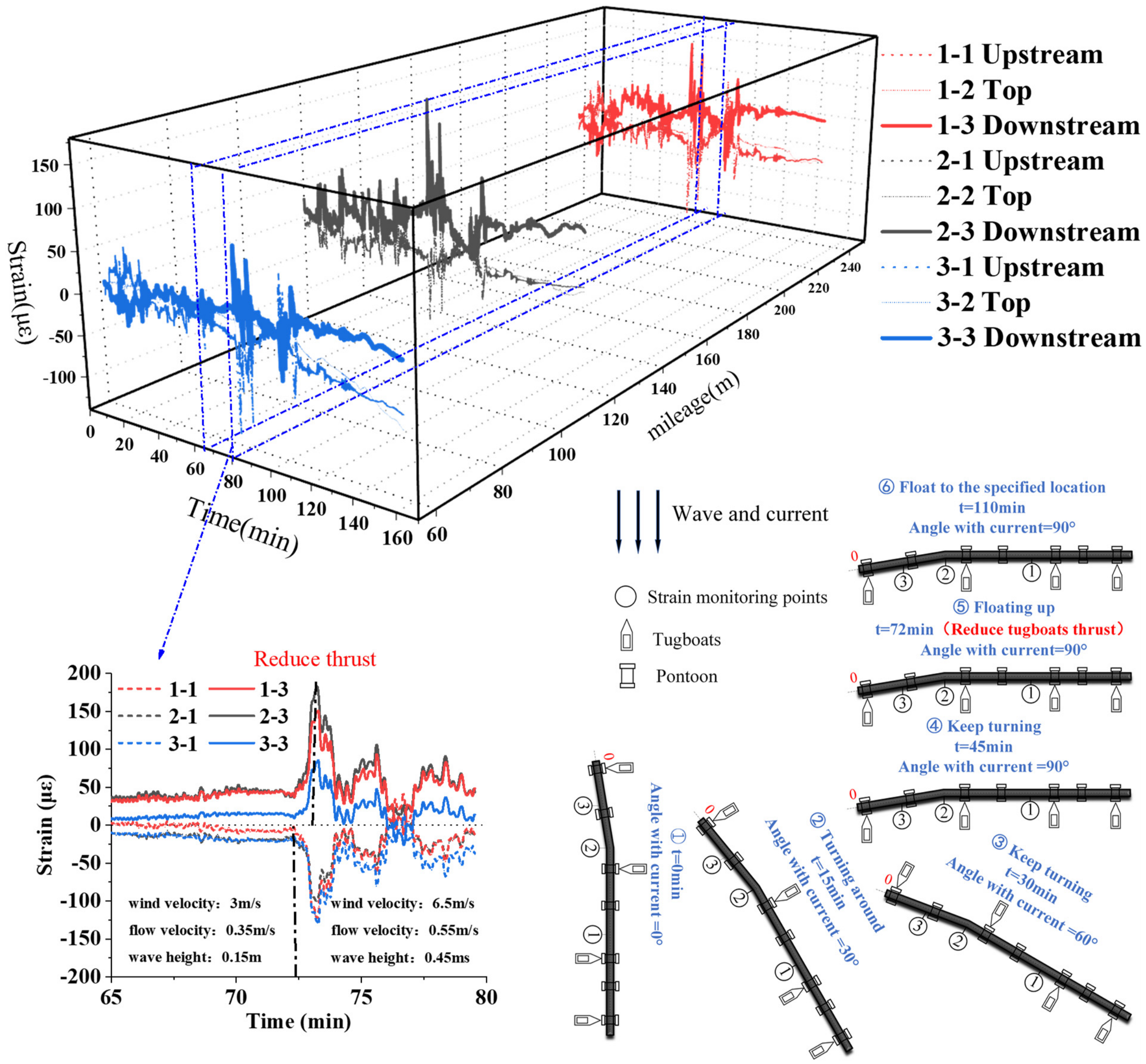

Figure 10. Dynamic floating construction of pipeline Section 1.

When the floating movement of pipeline Section 2 begins, the wind speed was 3 m/s, the flow velocity was 0.35 m/s, and the wave height was 0.15 m, the axis of the pipeline was along the direction of water flow. At 48 min of floating transportation, a strong wind suddenly appeared at sea, which was opposite to the floating transportation direction of the pipeline section. The wind speed was up to 6.5 m/s, the wave was up to 0.45 m, and the flow velocity was 0.55 m/s. At this time, the angle between the pipeline axis and the flow direction was about 90°. Dynamic construction is shown in Figure 11. Through monitoring, it is found that the strain at the water surface measurement point on the back of the pipeline continues to increase when it reaches 200 με, which is mainly caused by the increase in wind speed and flow velocity. The monitoring personnel immediately gave warning to the construction institution and reports the position of the maximum strain, informing the construction site operators to send an additional tugboat near Section 6 near the midpoint of the inclined pipeline section and continuously adjusting the position of the additional tugboat according to the monitoring data. Although the maximum strain of measuring point 5-2 at 55 min was 337.8 με, exceeding the alarm value, it was still within the safety range. After the additional tugboat starts to work, the overall strain of the pipeline gradually reduced and then becomes stable. Finally, the pipeline Section 2 was transported to the designated position safely.

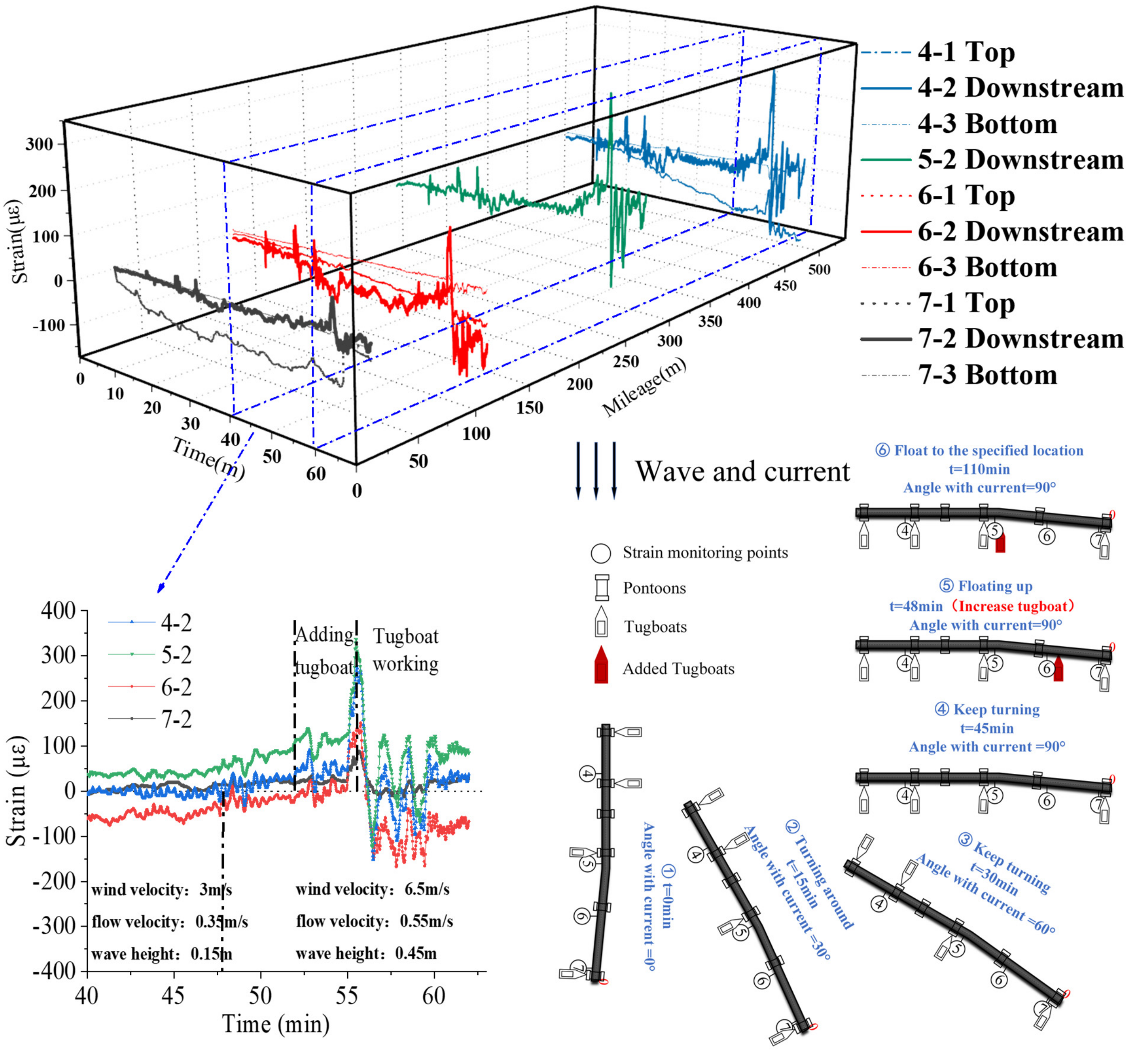

Figure 11. Dynamic floating construction of pipeline Section 2.

4.3. Modal Monitoring Results

The pipeline modal test adopted the environmental excitation method. The response signals of all the measurement points arranged on the pipeline were collected at once, and then the response signals were analyzed in the frequency spectrum to identify the modal parameters of the pipeline. The spectrum analysis adopted the power spectrum method to identify the system modal parameters by using the self-power spectrum of the pipeline response output and the mutual power spectrum amplitude of the reference point response input. The high-frequency acquisition could make the collected signal closer to the original signal and reduce the influence of industrial noise. As the floating time was as long as 3 h, the modal test of the floating process of pipeline segment 2 was divided into two stages, and the parameter balance was carried out respectively.

As shown in Figure 12 that A-1, B-1, B-2, C-2, D-1, D-2 are measured in the pipeline modal test. In the first stage of the test, at about 55 min, the time-history curve of acceleration increases significantly, which is the same as the time of strain surge. Since the sailing speed of the additional tugboat was not synchronized with that of other tugboats and the tugboats had been adjusting their positions, the movement of the extra tugboats had a temporary impact on the steel pipeline and the waves and flows near the pipeline. Therefore, there are some big fluctuations in the acceleration time-history curve between 55–93 min, among which the acceleration time-history curve at 62 min and 92 min has a large increase, but the duration is short.

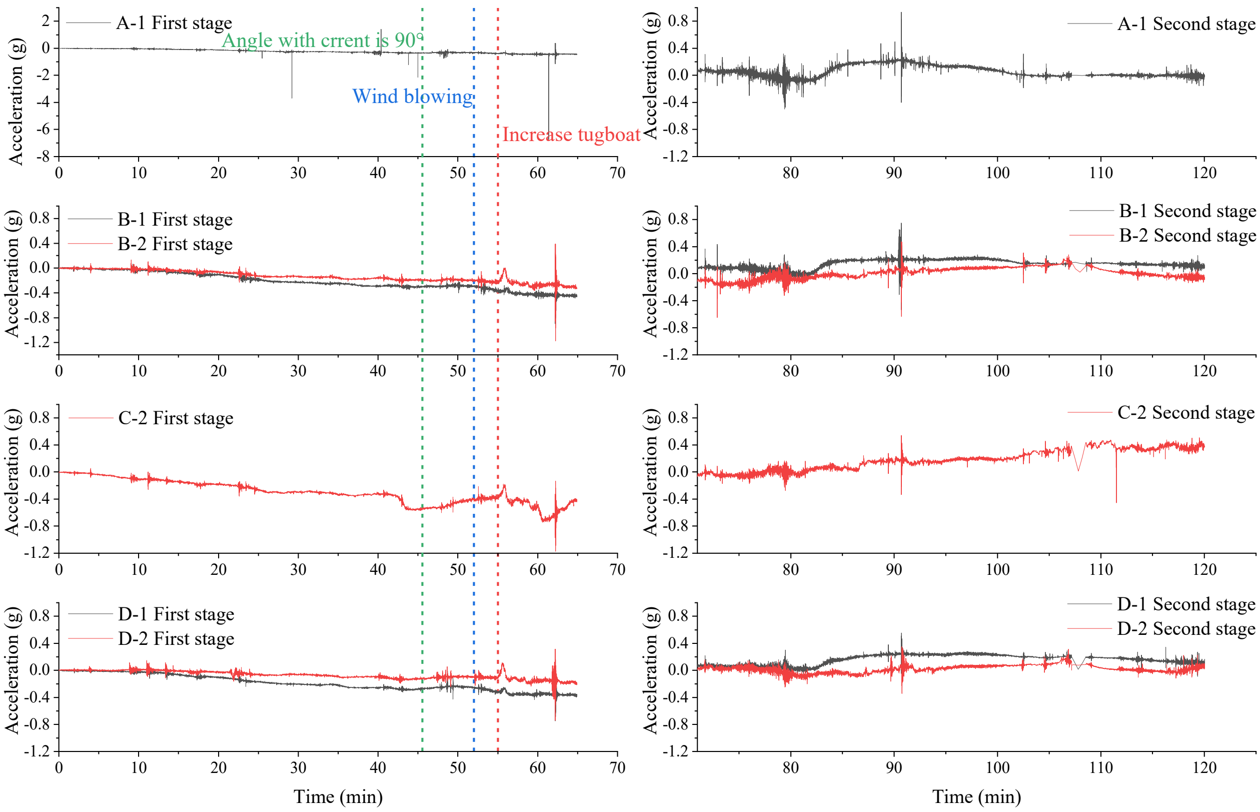

Figure 12. Data diagram of floating vibration of pipeline segment 2.

As shown in Figure 13 that according to the spectrum analysis, from the beginning of the floating movement to the wind rise, the horizontal and vertical first-order vibration frequency is 16.602 Hz, the frequency changes with a small increase to 17.578 Hz after adding a tugboat. At the beginning of floating transportation, the axis of the pipeline was parallel to the direction of the water flow, and the amplitude was the smallest. When the pipeline angle was transferred to 90°, the amplitude increased slightly, and the amplitude reached the maximum value after the wind rose. Then the tugboat was added, and the amplitude of the pipeline decreased significantly while the frequency increased.

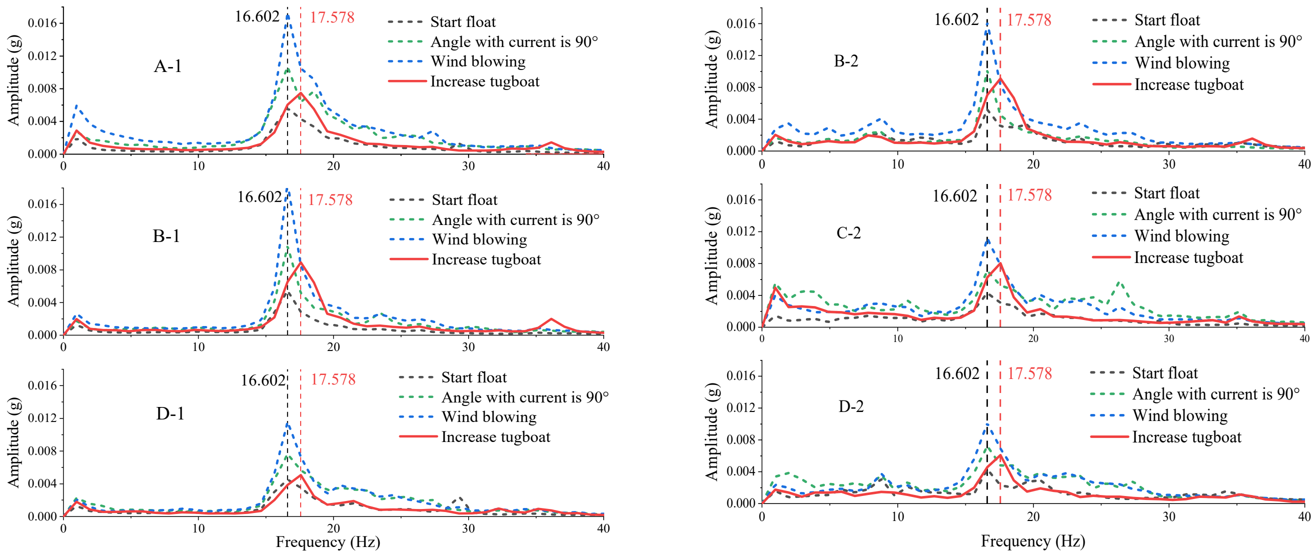

Figure 13. Frequency spectrum of pipeline segment 2 floating transport.

During the whole process of floating transportation, on-site real-time monitoring and dynamic construction reduced the impact of abrupt weather on the vibration of the pipeline, and the monitoring results show that there is no resonance phenomenon with excessive amplitude. All these further verify the rationality of the dynamic construction scheme based on the timely feedback of monitoring data.

5. Discussion

1. During the floating transportation of pipelines 1 and 2, the strain of the upstream and the downstream was obviously greater than that of the top, which was because that the upstream and the downstream were directly affected by water flow and waves, while the top part was less affected. In addition, the strain at the bent point of the pipeline was also larger than that of other parts. The bend point was not only affected by the vertical action of water flow and waves, but also affected by the component force transmitted by the bend section.
2. Floating posture and wind speed will affect the amplitude of the pipeline, but not the vibration frequency of the pipeline. However, increasing the number of tugboats will increase the vibration frequency of the pipeline and decrease the amplitude. For the same vibration system, the amplitude may change, but the vibration frequency is unchanged. Floating posture and wind speed do not change the weight and stiffness of the pipeline structure (i.e., vibration system), but increasing or decreasing the number of tugboats will change the weight and stiffness of the whole structure composed of tugboats and steel pipelines.
3. The strain at the bending point of the pipeline must be paid special attention to during the dynamic construction of the floating pipeline. The construction institution shall reasonably arrange the number of tugboats according to the real-time monitoring data, pay attention to controlling the speed of tugboats and the size of the towing force, and prevent the damage of anticorrosive coating and the vibration damage of pipeline due to excessive bending strain.
4. Through the reasonable arrangement of tugboats and buoyancy tanks for the super-long pipeline, the dynamic construction of the long-distance floating process can be realized with on-site monitoring. Ensure that the deformation and vibration of the

steel pipeline during floating transport are within a safe range. The obtained data and conclusions can provide a useful reference for similar pipeline floating construction.

5. The limitation of the discrete sensor is that it can only measure a finite section of the structure and cannot cover the whole length. If conditions permit, construction institutions or researchers can use distributed optical fiber sensors to realize non-destructive monitoring of a full kilometer distance, with more accurate event identification and positioning capabilities and more accurate and timely early warning.

6. Conclusions

Considering that the floating process of super-long steel pipeline at sea is a nonlinear geometric large deformation problem and is very sensitive to the load. This paper conducts field monitoring and dynamic construction of the super-long steel pipeline offshore floating project to feedback the deformation state of the pipeline to the construction institution, enabling construction institutions to adjust construction operations. Strictly control the deformation of the pipeline to ensure the safety of the extra-long steel pipeline floating, and obtain valuably measured and analyzed data, which provides a reference for similar projects. The specific conclusions are as follows:

- In the process of floating transportation, the pipeline was under the stress state of the upstream and the downstream, and the strain of the upstream and the downstream was obviously greater than that of the top of the steel pipeline. The strain at the bend was larger than that at the straight section. The long-distance pipeline could also maintain good consistency in its stress state while floating. Therefore, in the process of construction and monitoring, special attention should be paid to the upstream, downstream and bend of the floating steel pipeline, to keep the force on the pipeline uniform.
- If other structures (such as tugboats) were not added, the vibration frequency of the pipeline would remain basically unchanged. The amplitude would increase with the increase of wind, wave and water flow, and decrease obviously with the increase of the number of tugboats. The number, position and speed of tugboats both affected the pipeline, so the tugboats must be adjusted reasonably in the construction operation.
- The offshore floating transport pipeline should be subjected to on-site strain and modal monitoring at the same time. The monitoring personnel should feedback the data to the construction institution in real-time, giving a warning when necessary, and use the monitoring data to guide the construction institution to adjust the construction plan reasonably and dynamically. To ensure the strain and anticorrosion coating of the steel pipeline are within a safe range during the floating transportation and prevent the vibration damage of the pipeline. If it is possible, distributed optical fiber sensors can also be used for full-length and overall non-destructive monitoring of the kilometer pipeline, its event recognition and positioning capability are more accurate and early warning will be more accurate and timely.

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