Research on Uneven Settlement of Tianjin LNG Pipeline Reclamation Section

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Abstract: In this paper, the Tianjin LNG pipeline reclamation section is selected as a case study on the analysis and control technology of uneven settlement in soft soil areas. Relying on detailed geological surveys and laboratory tests, combined with numerical simulation methods and automated monitoring methods, comparative analysis of different types of settlement data was carried out. For soft soil similar to the engineering geological conditions in the study area, the compressive modulus was estimated to be a set more precise formulas.

1. Introduction
At this stage, the reclamation and land reclamation project is developing rapidly, and it is becoming more and more important to solve the problem of uneven settlement during the implementation of the project. Therefore, China's Li Yukun [2] used the principle of consolidation compression to calculate and predict the settlement value of the reclamation foundation; Liu Lanlan [3] applied CAESARI to calculate and summarize the stress characteristics of the natural gas pipeline under uneven settlement conditions; Li Dongdong [4] used the non-linear finite element analysis software ADINA to analyze the pipeline under the condition of uneven settlement to obtain its stress situation. The research of the above scholars mainly focused on the uneven settlement of the pipeline under the condition of the soft ground in the reclamation section, and the research on the settlement of the pipeline in complex geological conditions is less. In this study, automatic monitoring was used to monitor the sections prone to uneven settlement in real time, combined with Flac3d software to conduct 3D modeling of representative sections in different regions of the site, and the accuracy of theoretical calculation results was verified by numerical simulation analysis methods. And by analyzing the deviation between the indoor calculation data, numerical simulation analysis data and on-site monitoring data, for the soft soil similar to the engineering geological conditions in the study area, a set of more accurate formulas is obtained for the estimation of its compression modulus.

2. Project Overview
The research line of this project starts from 1m outside the wall of the Tianjin LNG receiving station, south to the end of Hongqi Road, and then west to Nangang Sixth Street. The total length of the line is about 14km. The whole area was originally the sea surface, and the original landform was the underwater bank slope landform area in the shallow sea area of the estuary of the Dagang District Dujiang River Basin. It is now formed by reclamation and land reclamation.

3. Analysis and Processing of Monitoring Data
In this study, a total of two monitoring devices were installed, which were installed at the inflection point of the north-south and east-west directions and 80m north of the receiving station. We collect data four times a day at 6 hour intervals. Then summarize data once a day and send it regularly.
The maximum value of the data collected by the device is 222.29 mm, indicating that the maximum difference between the two points is 43.79 mm. At the same time, the data fluctuated greatly in mid-December. The minimum value of the collected data is 118.12 mm, which shows that the maximum differential displacement of the pipeline at this point is 60.38 mm. It can be obtained by analyzing the actual situation on the site that the project is located in the industrial park under construction in Tianjin Nangang. The pipeline is long and the buried depth is only 1.7 m. There are multiple construction sites around the inflection point of the pipeline that are under construction. The movement of large vehicles and machinery is the main reason for the large fluctuations in data.
The maximum value of the data collected by equipment two is 538.59mm, indicating that the maximum differential settlement of the pipeline at this point is 21.33mm. The minimum value of the collected data is the initial elevation value.

It can be seen from the analysis of the two sets of data that external factors make the data of device one fluctuate, and the maximum differential settlement is 43.79 mm. Although the current settlement rate is in line with the indoor expected calculation, in the later period we should do a good job of monitoring the section. The largest differential settlement of equipment 2 is only 21.33mm, the trend is relatively slow, and the settlement rate is in line with the indoor expected calculation.

4. Numerical Simulation Analysis

According to the field survey, combined with the indoor data, the spatial distribution characteristics of the pipeline reclamation section are obtained, and the three-dimensional model is established from the spatial distribution. In order to simplify the model, a simplified paragraph will be created by taking a representative paragraph at the junction of the surrounding areas of Zones A, B, and C1 and C2, respectively.

The lower limit of the depth of the foundation compression layer is taken at the point where the additional stress of the foundation is equal to 20% of the self-weight stress, that is, \( \sigma_z = 0.2 \sigma_c \). Because the compressibility of the soil layer at this depth is still high, the final calculated depth is \( \sigma_z = 0.1 \sigma_c \). From the laboratory test data, static penetration test and related reclamation data calculation, it can be seen that within 80m below the base surface is the calculation depth of the lower limit of the vertical additional stress of the foundation of the pipeline surrounding the pond. Therefore, the vertical direction (Z axis) of the above models is 80m.

Area A represents the model length (X axis) 100m and width (Y axis) 30m. The model can be divided into three layers: the first layer is the reclamation silt soil with an average thickness of 6.13m and the sand filling; the second layer is the natural marine silt soil with an average thickness of 13.37m; the third layer is an average thickness of 60.5m of silty clay and silty clay.

Area B represents 100m in length (X axis) and 40m in width (Y axis). The model can be divided into three layers: the first layer is a reclamation layer with an average thickness of 7.1m, and the muddy soil is washed and filled; the second layer is an average thickness of 12.9m, which is partially mixed with a thin layer of silt and artificial marine sand silt soil; the third layer is silty clay and silty clay with an average thickness of 60.0m.

![Fig.3 Representative Models of Zone A and Zone B](image-url)
The model length (X axis) at the junction of C1 and C2 enclosures is 204m (X axis), which is 100m in C1 (X axis), 100m in C2 (X axis), 4m in height (X axis), and height (Z axis) 2m), width (Y axis) is 30m. The C1 area model can be divided into three layers: the first layer is the flushing sand with an average thickness of 7.0m and the reclamation layer with the muddy soil; the second layer is the natural marine muddy soil with an average thickness of 12.0m; the third layer is silt and silty clay with an average thickness of 61.0m. The C2 area model is divided into three layers: the first layer is erosion sand with an average thickness of 6.1m and the reclamation layer with muddy soil; the second layer is natural marine muddy soil with an average thickness of 13.4m; the third layer is silt and silty clay with an average thickness of 60.5m.

![Fig.4 Model of the Junction between Area C1 and Area C2](image)

It can be seen from the three-dimensional displacement cloud map of area A: the deformation is mainly located at the top of the model (Z = 80) and near the pipeline (Z = 77.5). The overall
longitudinal average displacement of the pipeline is 1000 mm, and the horizontal displacement value is ignored. The settlement observation points in this area are respectively arranged at the two ends of the pipeline on both sides, with settlement values of 1575mm and 1680mm. On-site static penetration equipment (No. 30 and No. 40) correspond to two settlement observation points one by one. The final average settlement value is estimated by four indoor empirical algorithms. The penetration number 30 (CT30) is 1994.7mm, and the penetration number 40 (CT40) is 2099mm.

Table 1. Comparison Table between the Numerical Simulation Monitoring Value of Area A and the Estimated Value of CPT Method

| Analog Points | Monitor Analog Values | Touch Point | Estimated Value |
|---------------|-----------------------|-------------|-----------------|
| JC1           | 1526mm                | CT30        | 1994.7mm        |
| JC2           | 1630mm                | CT40        | 2099mm          |

Fig.6 3D Displacement Cloud Image of the Zone B

It can be seen from the three-dimensional displacement cloud map of area B: the top of the model (Z = 80) and the pipeline (Z = 77.5) are the places where the deformation is most concentrated. The average value of the overall longitudinal displacement of the ground can reach 3000 mm, and the horizontal displacement value is ignored. The settlement observation points in this area are respectively arranged at the two ends of the pipeline, and the settlement values are 2440mm and 2064mm. The final average settlement value is estimated by four indoor empirical algorithms. The probe number 15 (CT15) is 3071.9mm, and the probe number 20 (CT20) is 3098.5mm.

Table 2. Comparison Table between the Numerical Simulation Monitoring Value of Area B and the Estimated Value of CPT Method

| Analog Points | Monitor Analog Values | Touch Point | Estimated Value |
|---------------|-----------------------|-------------|-----------------|
| JC1           | 2392mm                | CT15        | 3071.9mm        |
| JC2           | 2016mm                | CT20        | 3098.5mm        |
Fig. 7 Three-dimensional Displacement Cloud at the Surrounding Fields of C1 and C2

It can be seen from the three-dimensional displacement cloud maps at the enclosing areas of C1 and C2: the top of the model (Z = 80) and the pipeline (Z = 77.5) are the places where the deformation is most concentrated. The horizontal displacement value is ignored. A settlement observation point is arranged at the end points on both sides of the C1 and C2 areas respectively, and the settlement values are 1075.6 mm and 1624.6 mm, respectively. On-site static sounding No. 47 and No. 49 correspond to the settlement observation points on both sides. In addition, a settlement observation point was also set up at the junction of the surrounding fields, corresponding to the site static sounding number 48, and the settlement value was 950.5mm. The final average settlement value is estimated by four indoor empirical algorithms. The probe number 47 (CT47) is 1140.5mm, the probe number 49 (CT49) is 1934.8mm, and the probe number 48 (CT48) is 978.2mm.

The comparison between the simulated value and the indoor estimated value shows that the difference between the simulated value and the indoor empirical algorithm estimate is not large. During the establishment of the model, the site selection is in a representative section, which makes the model simpler and simplifies the calculation. By comparing the data fed back from the on-site automated monitoring system, it can be seen that the actual observed values are within the range of theoretical calculations and simulated values, which is in line with expected calculations. By analogy, the indoor estimates and numerical simulation results are also accurate and effective for other areas of the site.

5. Modified Equation of Estimation of Compressive Modulus of Clay or Soft Soil

When checking the final settlement of the foundation along the pipeline, the compression modulus estimation equation proposed by the Fourth Academy of Railways was selected:

\[ E_s = 4.13p_s^{0.687} \quad (p_s \leq 1.3 \text{ MPa}) \]
\[ E_s = 2.14p_s + 2.17 \quad (p_s > 1.3 \text{ MPa}) \]

Table 3. Analysis and Comparison Table of Theoretical Data and Monitoring Data in Area A

| Sub Option                  | Theoretical Data | Monitoring Data |
|-----------------------------|------------------|-----------------|
| Relative Settlement Displacement (mm) | 257.6            | 27.58           |
| Time Span                  | 20 years         | 240 days        |
| Settling Time Correction Factor | 0.7              | 1.5             |
| 1 Year Effective Relative Settlement Value (mm) | 180.32           | 41.34           |
| Distance between Two Points (m) | 100              | 25              |
| Relationship between Settlement and Distance (mm/m) | 1.803            | 1.655           |
According to the analysis and comparison of the theoretical data and monitoring data in Area A, the correction coefficient of the compressive modulus of clay or soft soil (ps≤1.3 MPa) of the Fourth Railway Institute can be obtained as 0.918.

| Sub Option                              | Theoretical Data | Monitoring Data |
|-----------------------------------------|------------------|-----------------|
| Relative Settlement Displacement (mm)   | 578.57           | 17.51           |
| Time Span                               | 20 years         | 180 days        |
| Settling Time Correction Factor         | 0.7              | 1.75            |
| 1 Year Effective Relative Settlement Value (mm) | 405.26 |
| Distance between Two Points (m)         | 300              | 25              |
| Relationship between Settlement and Distance (mm/m) | 1.350 |

According to the analysis and comparison of the theoretical data and monitoring data in the area B, the correction coefficient of the compressive modulus of clay or soft soil (ps> 1.3 MPa) of the Fourth Railway Institute can be obtained as 0.908.

Calculate the indoor test results by reversing the correction value and find that the correction value is always between the original theoretical value and the simulated value. This shows that through the correction calculation, the indoor theoretical calculation value and the numerical simulation result become closer than before the correction. At the same time, it also shows that our revision process and results are completely correct. Substitute the correction coefficients into the corresponding original compression modulus estimation equations:

\[ E_s = 4.13p_s^{0.687} \quad (ps \leq 1.3 \text{ MPa}), \text{ The correction factor is 0.918}; \]
\[ E_s = 2.14p_s + 2.17 \quad (ps > 1.3 \text{ MPa}), \text{ The correction factor is 0.908}; \]

The final correction equation is obtained as follows:

1. \[ E_s = 3.79p_s^{0.687} \quad (ps \leq 1.3 \text{ MPa}) \]
2. \[ E_s = 1.94ps + 1.97 \quad (ps > 1.3 \text{ MPa}) \]

6. Conclusion

This article explores the problem of uneven settlement of the Tianjin LNG pipeline reclamation section, and obtains the settlement data of the rock and soil layer of the reclamation section through automated monitoring and numerical simulation, and then combines the preliminary indoor calculation results to finally discuss the results and obtain the following several conclusions: (1) By establishing models for the representative sections of the three large areas of the site, it can be seen that the simulated values are close to the indoor estimated values. (2) Through analysis and comparison with the data from the on-site monitoring system, the compressive modulus of soft clay or soft clay in the engineering geological conditions of the Tianjin LNG pipeline reclamation area is estimated. (3) Due to the limitation of the current data volume, in order to obtain a more accurate correction equation, additional monitoring equipment and longer monitoring time should be added.

References:

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