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Deflection behavior of the steel pipe-jacking in soft soil seabed

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ABSTRACT: The pipe-jacking method is a kind of efficient trenchless technology to install pipelines, especially for the pipeline going through the downtown of the city or the rivers. As the important part of the water supply project in Xiamen, two steel pipes with 2.2 m diameter would be installed to cross the strait between Xiamen Island and the mainland. Considering the navigation channel in the strait, complicated stratum in site, and construction techniques and costs, the pipe-jacking method is adopted. Since the longitudinal stiffness of the steel jacking pipes is relatively lower than that of the reinforced concrete jacking pipes, the upheaval deflection is more likely to occur on the steel pipes with small buried depth. In this study, the upheaval deflection of the steel jacking pipes in the soft soil seabed is analyzed and controlled. The total jacking distance from #2 working well to #5 working well in this project is 816 m. During the jacking stage, obvious upheaval deflection occurs in the part under channel area, in where the buried depth of pipes is only 2.96 m (i.e. 1.3D). Such upheaval movement also affects the adjacent pipe sections, which causes that the total upheaval length of pipe is about 260 m. Considering the geological condition and influence of the wave, the qualitative and semi-quantitative analysis is carried out to investigate the major factors causing the upheaval deflection. Result shows that the resistance of soil is too small to offset resultant upward forces. Furthermore, the jacking force will contribute to the increase of upheaval after the upward deflection occurs. Therefore, surcharging method is proposed to reduce the upward deflection of the steel jacking pipes. The field measurement shows that the deflection of steel pipes decreased after loading in pipes. This study will provide the beneficial reference for the design and the construction of the steel jacking pipes in soft soil seabed.

1 INTRODUCTION

For pipelines buried under the sea, the disadvantages will exist either they are placed on the seabed or embedded in the seabed. For instance, corrosion on pipes is inevitable in both conditions, besides the buoyancy and the wave loading have great influence on the pipes because of shallow buried. In addition the sinking ship or other accidents might endanger the safety of the pipes as well. The jacking pipes can overcome the above shortcomings in some ways. The buried depth of the jacking pipes is usually deeper than that of the shallow buried pipes. Therefore the risk of the physical damage from surroundings or accidents can be reduced. Since all excavations are underground, the construction has very low environmental impact and it does not affect navigation and other operations on the sea. Moreover, the pipe-jacking method has slight disturbance in the seabed to ensure the soil cover maintaining compacted at the most extent. According to the demands and conditions of the project, good adaptability of large diameter steel pipes, complicated stratum, mixed straight and curved jacking, and low cost, all of these factors indicated that the pipe-jacking method was the best choice at that time.

However, no matter steel buried pipes or steel jacking pipes, due to their low longitudinal stiffness, upheaval is a serious accident which is prone to occur if there is not enough resistance to upward movement of pipes. This is more conventional during earthquakes, such as the buckling of water supply pipelines during the 1990 Manjil earthquake in Iran, and the 3 m offset of a 2.2 m diameter pipeline caused by strike-slip faulting during the 1999 Izmit earthquake in Turkey (Rojhani et al. 2012). Previous researches paid more attention on the buried pipe. Yun & Kyriakides (1985) built the model of the pipes under sea as a long heavy beam on a contacting surface. The reacting surface was modeled first as an elastic foundation and subsequently as a rigid foundation, with the additional constraint it only reacted to compressive loads. Andreuzzi & Perrone (2001) deduced the analytical evaluation of the upheaval buckling critical load for submarine pipelines due to a temperature gradient. Schupp et al. (2006), Cheuk
et al. (2008) & Byrne et al. (2013) conducted a series of experiments and theoretical analysis. The mechanism of upheaval buckling for buried pipelines in sand was explained from different aspects. Palmer et al. (2003) suggested shear zones enhanced the uplift resistance (the maximum force per unit length) of buried pipes through centrifuge modelling tests with rock, dense sand, fine sand and a fine cohesionless silt. Thusyanthan et al. (2008) investigated the effects of backfill cover and rock-dump thickness on the uplift resistance for buried pipes using natural marine clay. The resistance of soil cover, the vertical pipe displacement, and excess pore pressure changes were measured and analyzed. In comparison with steel buried pipes, upheaval is more likely to happen in steel jacking pipes bearing axial forces directly on two ends. Whereas there are few studies involved in the upheaval deflection of steel jacking pipes in the jacking stage under soft soil seabed.

In this study, the steel jacking pipes with 2.2 m outer diameter were jacked through the strait in the soft soil seabed for water supply, which also encountered the problem of upheaval deflection during construction. The reasons are analyzed and relevant measures apply to control the upheaval deflection. Results of measurement show that remedial treatment is effective.

2 PIPE-JACKING PROJECT

2.1 Project background

There are two pipelines abreast crossing the strait under the seabed for water supply in Xiamen using pipe-jacking method. The overall lengths of them both are 1905 m. The outer diameter of each pipeline is 2.2 m and the wall thickness is 20 mm. The first plan intended to jack the pipes from #1 working well at Jimei to #2 working well at Gaoqi directly. However, because of the shallow buried bedrock, the pipelines were blocked on half way. A large number of bedrock was found in the supplemental geological exploration right in the jacking direction. Therefore #3 working well and #4 working well were added in the modified scheme to avoid crossing the hard rock (Fig. 1). For the convenience of construction, #5 working well was finally set between #4 working well and #2 working well so that the two pipes could be respectively jacked from #4 working well and #2 working well to #5 working well at the same time.

The distance from #2 working well to #5 working well is 860 m, whereas the actual jacking distance is 816 m. The main channel (0 + 40 m to 0 + 180 m) locates right between #2 working well and #5 working well and it is closer to #2 working well (Fig. 2).

2.2 Geological condition

According to the geological exploration report, the area is divided into six geological layers as shown in Table 1. Among them, the layer 2-1 is almost composed of mucky soil. This research only focused on the upheaval deflection of the pipeline occurred in the jacking stage. Hence the strength parameters of soil were obtained from the results of the consolidated quick shear tests without considering long-term deformation. The pipes successively crossed 816 m layer 2-1 as it proceeds from #2 working well to #5 working well.

2.3 Engineering accident

The maximum depth of layer 2-1 is about 15 m, as shown in Fig. 2. According to the demand of the pipe-jacking project, the elevation of the deepest dredging was −7.400 m. Thus the seabed got deeper due to the dredging. The deepest seabed reached nearly −10.500 m while the top of the steel jacking pipes in the design was −9.700 m in the channel area. To meet the requirement of the minimum thickness of the soil cover and the minimum depth of the navigation, the proper backfill in the channel area before jacking was necessary.

The backfill can be divided into two forms for different sections in this project, as shown in Fig. 3(a) and (b). At the standard section of 0 + 265 m to 0 + 365 m, i.e. for relatively shallow seabed, the backfill first was leveled up to −6.400 m, and dams made of stones in reinforcement cages were built on both sides of two pipelines. Then the space between two dams was filled with sand. Finally riprap revetment was used to prevent landslide from happening and strengthen the dams on the weak side. Thus scouring to the backfill could be reduced as well. Within the scope of 100 m standard section, such backfill maintained the elevation of −2.300 m. In the adjacent area, slope backfill was used based on the actual terrain of the seabed. At the standard section of 0 + 40 m to 0 + 145 m, i.e. for

<table>
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<tr>
<th>Number</th>
<th>$\gamma_s$ (kN/m$^3$)</th>
<th>$e$</th>
<th>$w_m$ (%)</th>
<th>$I_L$</th>
<th>$c$ (kPa)</th>
<th>$\varphi$</th>
<th>$N_{63.5}$</th>
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<td>7.3</td>
<td>62.7</td>
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<td>0.00</td>
<td>60</td>
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*Note: $\gamma_s =$ Unit weight of soil; $e =$ Void ratio; $w_m =$ Moisture content; $I_L =$ Liquid index; $c$, $\varphi =$ Cohesion and friction angle under consolidated quick shear; $N_{63.5} =$ Blow counts of SPT.
the deepest section, riprap directly covered the backfill and its thickness was 1.50 m so that the elevation of the deepest seabed reached −6.740 m. The effective depth of the soil cover was about 2.96 m (1.3 D) above the top of the pipelines which had met the minimum buried depth in theory.

A string of welded continuous steel pipes were jacked from #2 working well. Although the seabed was covered with the backfill beforehand, upheaval still occurred. Taking the west pipeline for instance, in the initial jacking stage, the tendency of upward deflection was obvious. Through the pipe-jacking machine constantly adjusting the jacking direction, the jacking axis recorded in Fig. 4 depicted the height of upheaval still increased rapidly after jacking 60 m where the pipes had reached the area of the shallowest soil cover.
The intermediate jacking station was first opened at the location of 152 m far from #2 working well due to the greater jacking force needed to adjust the jacking direction. When the total jacking distance reached 208 m on May 25th, the maximum height of upheaval was 61.2 cm. However, three days later, on May 28th, the total jacking distance was 232 m and the intermediate jacking station was moved to the location of 176 m. The maximum height of upheaval increased to 69.8 cm. The maximum upward deflection increased by 8.6 cm within 24 m jacking distance. It was a signal to show the safety of the whole pipeline had been endangered.

After normal jacking nearly 400 m, the pipeline had passed through the shallowest soil cover area (the channel area), and upheaval occurred on both of the east pipeline and the west pipeline. The upheaval section was exactly in the navigation channel area and the nearby shallow buried areas, approximately ranged from 0 + 0 m to 0 + 260 m. The height of upheaval was beginning to decrease and kept stabilize after 0 + 260 m section. For the east pipeline, the maximum height of upheaval was 41.9 cm, as shown in Fig. 5. For the west pipeline, the maximum height of upheaval was 62.1 cm, as shown in Fig. 6. The section of the maximum upheaval located in the channel area, where 150 m far from #2 working well. The deflection shapes of two pipelines were almost the same. As the depth of the soil cover increased, the upheaval deflection for two pipelines began to decrease. It demonstrated that the shallow soil cover could not provide sufficient resistance to prevent pipes from upward deflection.

The research will mainly focus on the upheaval section. The west pipeline has been partially shown in Figure 2 as a sample (the condition in the east is analogous).

3 DISCUSSIONS

3.1 Deflection analysis

The jacking pipes should float in the slurry under ideal conditions. Only the gravity was downward force and the buoyancy offered by the water was upward force for the pipeline.

\[ G_p = \gamma_p S_p = 78.5 \times (1.1^2 - 1.08^2) \times 3.14 \]
\[ = 10.75 \text{ kN/m} \]
\[ F = \gamma_w S = 10 \times 1.1^2 \times 3.14 = 37.99 \text{ kN/m} \]

where \( G_p \) = the weight of the pipe per unit length; \( \gamma_p \) = the unit weight of the pipe; \( S_p \) = the sectional area of the pipe; \( F \) = the buoyancy per unit length; \( \gamma_w \) = the unit weight of the water; \( S \) = the area within the outer diameter of the pipe.

Apparently, the buoyancy was greater than the gravity, so the upward deflection occurred. Nevertheless, the large deflection appeared in the seabed without visible damage for the pipelines and the seabed after jacking almost 400 m. Actually the seriously affected section approximately accounted for 260 m. The theoretical buckling critical load of 260 m pipe under the water-earth pressure (138.57 kPa) is approximately 3081 kN in this case. It is greater than the maximum actual jacking force 2000 kN during that period. Hence no buckling happened. It implied the soil cover provided resistance.

As following five field measurements were carried out during the jacking process after the pipeline had passed through the navigation channel area. The measured data of the axial deflection on the vertical plane for the pipelines are partially plotted as Fig. 5 and Fig. 6. The designed axis is consistent with the axis of value 0 (the horizontal dash line). The position of every measuring point denotes deviation orientation and distance from the designed axial on the vertical plane. The slight lateral deflection on the horizontal plane (the maximum deflection of 7.0 cm on the east and 7.3 on the west) comparing with the height of upheaval can be omitted. The measurement started at the location of 0 + 0 m (#2 working well) and ended at 0 + 816 m (#5 working well). Because of slight upheaval in the deep buried section, Fig. 5 and Fig. 6 only exhibit the section from 0 + 0 m to 0 + 450 m.

The first measurement was conducted when pipes were normally jacked on approximate 400 m. The maximum upheaval section and the large deflection area coincided with the shallow buried area. The maximum heights of the upheaval were 41.9 cm on the east and 62.1 cm on the west respectively, which was far...
beyond the design allowable range and it endangered safety of the project, while for the area with deep soil cover, small deflection could meet the design allowable range. Because there was no leak or damage on the pipelines, in all probability, the reason was that the shallow soil cover and the self-weight of the pipelines could not resist the buoyancy effectively.

Both of Palmer et al. (2003) and Thusyanthan et al. (2008) analyzed the resistance of the soil to the buried pipe through centrifuge tests. For normal consolidation soil, the resistance comprised the soil weight above the top of the pipe, the shear force on planes extending from the pipe shoulders towards the ground surface and the self-weight of the pipe (see Fig. 7). In this case, the buoyancy was known as the mainly upward force.

Based on the aforementioned theory, the resistance and the buoyancy can be calculated below:

\[ W' = \gamma'HD = (15.9-10)*2.96*2.2 = 38.42 \text{ kN/m} \]

\[ \tau = c + \sigma'_s \tan \phi = c + K' \tan \phi = c + K' \tan \phi \]

\[ \Gamma = \int_{0}^{H} (c + \tau) \, dz = cH + \frac{1}{2}K' \tan \phi \]

\[ = 0.43*2.96+0.5*0.8*(15.9-10)*2.96^2*12.19 \]

\[ = 5.74 \text{ kN/m} \]

where \( W' \) is the effective weight of the soil above the top of the pipe; \( \gamma' \) is the effective unit weight of the soil; \( H \) is the height of shear banding; \( D \) is the outer diameter of the pipe; \( \tau \) is shear pressure on the shear banding; \( c \) is effective cohesion; \( \sigma'_s \) is the horizontal stress in the earth; \( \phi \) is effective internal friction angle; \( K \) is the coefficient of lateral pressure; \( \sigma'_s \) is the vertical stress in the earth; \( \Gamma \) is the total shear stress.

Moreover, Xu et al. (2012) suggested tides induced pore pressure redistribution around the pipe which was buried in the seabed. The additional upward force changed with time acted on the pipe. The maximum additional upward force was approximate 30% of the static buoyancy. Thus,

\[ F_p = W + 2 \Gamma + G_p = 60.65 \text{ kN/m} \]

\[ \lambda = \frac{F_R}{F_{wp}} = 1.228 \]

3.2 Treatment and effect

Although the safety factor \( \lambda \) is exactly greater than 1.0, it still cannot ensure the safety of the project. Once the actual axis deviated from the designed axis, the jacking force would intensify the upheaval deflection. In addition, the disturbance in the soil and the non-uniform grouting pressure might also generate the upward force in the jacking stage.

Since the jacking force needed to constantly increase, controlling upheaval is important to prevent buckling. Increasing the depth of the soil cover may be hard; however increasing the self-weight of the pipes is comparatively easy. A large number of sand and steel was on the construction site. Stacking them up in the pipelines at the upheaval section could effectively increase the self-weight of the pipelines.

Because of limited space in the pipeline and being convenient for following construction, sand was put on the bottom of the pipeline while steel was on the two sides, as shown in Fig. 8. The passage was in the middle for transportation. The average every meter of the pipeline loaded 1.7 tons sand with 0.70 m height and 3.0 tons steel. These materials were moved backward as pipes jacked forward and they were always maintained in the upheaval area. At the same time, the jacking direction was adjusted to slight downward through increasing jacking forces at the top of the pipe-jacking machine and decreasing jacking forces at the bottom. Thus the pipe-jacking machine sinking in advance could offset a part of upheaval. In addition, increasing the grouting pressure on the top of the pipeline was conducive to reduction of upheaval.

The additional loads led to vanishing of the shear force extending from the pipe shoulders towards the ground surface in the earth. The total resistance changed to be:

\[ F_R = W + G_p + G_L = 96.17 \text{ kN/m} \]

where \( G_L \) is the weight of the additional load per unit length.

Four times subsequent measurements were carried out after jacking beyond 100 m every time and the last one was at the time of finishing the entire jacking. The maximum upheaval height finally respectively reduced to 14.9 cm on the east and 14.7 cm on the west (see Fig. 5 and 6). Taking the section of 0 + 150 m as an example shown in Fig. 9, the first data were recorded without conducting the loading treatment for the east and the west pipeline. The subsequent four data were recorded after implement of the loading treatment. The trend of the upheaval deflection suggests that upheaval
Figure 8. Loading in the pipeline.

Figure 9. The upheaval deflection in $0 + 150$ m with time.

decreased with time after the treatment was carried out. The height of upheaval met the requirement of the standard after completing jacking at last. Then the cement slurry was grouted and it made the initial slurry around the pipeline solidified. Together with fixing two ends and weld, the pipeline had good integrality. Thus the upheaval deflection was controlled. Finally sand and steel could be removed.

4 CONCLUSIONS

The upheaval deflection and the remedial treatment in the project of undersea large diameter steel pipe-jacking are presented. Since the jacking force is conducive to upheaval, the condition for jacking pipes is more complex than that for buried pipes. Tides induce greater upward force because of pore pressure change and liquidation. Therefore the undersea surroundings are more complex than the land surroundings. The main cause of the accident is that resultant downward forces for the pipeline cannot resist resultant upward forces. For this reason, two methods can be proposed to enhance the resistance to reduce the upheaval deflections. One is increasing the depth of soil cover or strengthening the in-situ soil, and the other is increasing the self-weight of pipes. In this case, by means of proper weight distribution in the pipelines, the maximum upheaval height respectively reduced from 41.9 cm to 14.9 cm on the east and from 62.1 cm to 14.7 cm on the west.

In summary, the upheaval accident in the pipe-jacking project is analyzed based on qualitative and semi-quantitative methods, and the remedial treatment is effective. The case can serve as a reference for effective design and safe construction of similar steel pipe-jacking projects in soft soil seabed.

REFERENCES


