Engineering Structures 59 (2014) 210–219

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Analysis and remedial treatment of a steel pipe-jacking accident in complex underground environment

Liang Zhen [a], Jin-Jian Chen [a], Pizhong Qiao [a,b,*], Jian-Hua Wang [a]

[a] School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China
[b] Department of Civil and Environmental Engineering, Washington State University, Sloan Hall 117, Pullman, WA 99164-2910, USA

ARTICLE INFO

Article history:
Received 22 July 2013
Revised 8 October 2013
Accepted 14 October 2013
Available online 3 December 2013

Keywords:
Complex underground environment
Steel pipe-jacking
Buckling
Engineering accident
Remedial treatment

ABSTRACT

Steel pipe-jacking has been widely used in the construction of water supply and sewage pipelines because of its self-sealing qualities, ability to withstand high pressure and lower environmental impact. The trend in steel pipe-jacking is towards larger diameters, longer drive lengths, and better adaptation to more complex underground conditions. Steel pipe-jacking, in which a flexible pipe is used, is different from concrete pipe-jacking where a rigid pipe is used. With increasing diameters and drive lengths, the mechanical characteristics of deep-buried steel pipe-jacking in complex underground conditions have presented new challenges for designers. In this study, the forces involved and the stability of steel pipe-jacking are analyzed by examining an example of steel pipe-jacking in a complex underground environment. The causes of high deflection under elevated water and earth pressure and local buckling incidents are investigated by the finite element method. The results show that, in this particular case, confining pressure combined with jacking force leads to buckling. Two main remedial schemes are proposed: one is to increase the wall thickness of the pipe, and the other is to install stiffening ribs on the pipe where high deflection occurs. The effect of the two remedial schemes is presented and evaluated. In particular, various stiffening ribs are used in different deflection sections with grouting to decrease friction and lower the corresponding axial jacking force. This approach demonstrates that the structural strength of the pipeline has met the requirements after the rectification action is taken. The analysis and remedial treatment for this case study will provide a reference for effective design and construction of similar steel pipe-jacking.

1. Introduction

Pipe-jacking is the technique for installing pipelines through the use of the hydraulic jacking of a pipe string, operated either mechanically or manually for excavation in front, from a launch shaft to a receiving shaft. Jacking pipes are added one after another to the end of the pipe string as the proceeding pipe advances. This procedure is repeated until the pipe string reaches the receiving shaft [1,2], as shown in Fig. 1.

The pipe-jacking method, as a type of trenchless technology for laying pipelines, has the characteristics of good integrality, low comprehensive cost, short construction period, low environmental impact, and low maintenance. It has been in use for several decades, and much practical experience and development has gone into the design of equipment and techniques [3]. These range from manual excavation to mechanized excavation, from earth pressure balance tunneling machines to slurry pressure balance tunneling machines, from reinforced concrete pipes and steel pipes to PVC pipes and other types of composite material pipes, and they also involve the use of slurry and intermediate jacking stations [4]. These developments in pipe-jacking technology have led to its use in small diameter, short drive length, straight pipe-jacking to large diameter, long drive length and curved pipe-jacking. Nowadays, pipe-jacking is widely used in many fields.

Despite these developments, designs for pipe-jacking are still conservative because the mechanical behavior of pipe–soil interaction presents a complicated problem for designers. Designers usually focus more on the jacking force needed, deflection of the pipe and the impact on its surroundings. For steel pipe-jacking, structural stability cannot be ignored, especially under combined loading.

Palmer and Baldry [5] first raised the concern regarding pipeline buckling that the expansion of a pipeline on account of raised internal pressure could induce buckling [6]. Upheaval buckling occurs in buried steel pipelines because fluid is usually pumped through the pipes at elevated temperatures causing the pipeline to experience thermal expansion which, if restrained, leads to an increase in the axial stress in the pipeline, possibly resulting in a

* Corresponding author at: Department of Engineering Mechanics, Shanghai Jiao Tong University, Mulan Building A903, Shanghai, 200240, PR China.
E-mail addresses: qiao@sjtu.edu.cn, qiao@wsu.edu (P. Qiao).

0141-0296/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2013.10.025

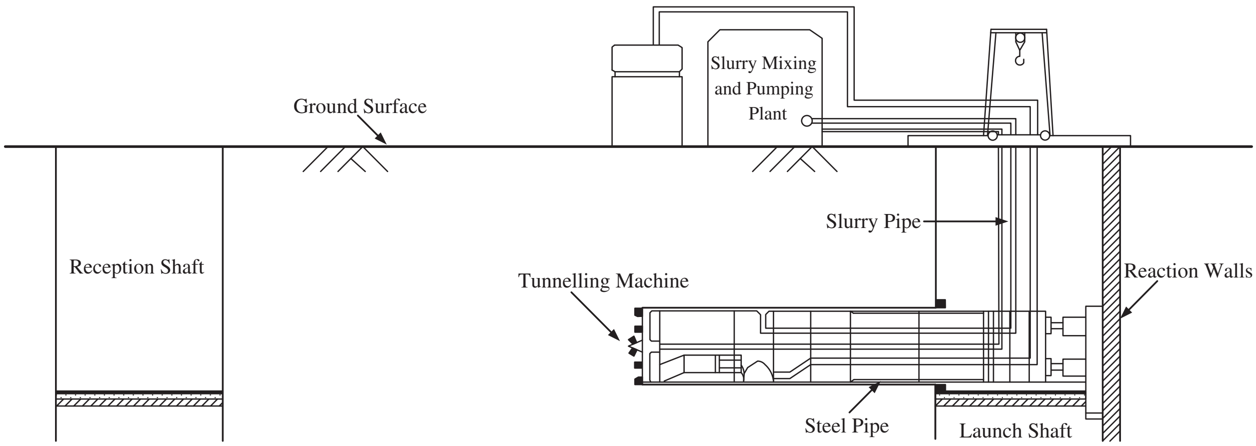

Fig. 1. Diagram of pipe-jacking.

buckling failure. A secondary phenomenon, particularly in loose silty sands and silts, involves flotation of pipelines within the backfill material, usually shortly after burial [7]. In addition, buckling of steel buried pipes also occurs due to movement of faults in the earth [8–10] and differential settlements [11].

The condition of the steel pipe during the jacking process is more complex than that of the buried pipe in the construction phase. The latter process involves first excavating a trench, and then laying steel pipes and covering with backfill. Only water and earth pressure, and buoyancy are usually considered. The steel jacking pipe also bears water and earth pressure and buoyancy [12]; but in addition, there is an axial jacking force from the hydraulic jacks, head resistance and frictional resistance from the soil. However, research on the structural stability of steel pipe-jacking is very limited in the existing literature.

This paper presents a steel pipe-jacking accident case which occurred in a water intake pipe below the bed of the Yangtze River. The analysis based on the finite element method (FEM) is introduced to analyze the deflection of the steel pipe-jacking pipes under high water and earth pressure. Rectification actions for the accident are then proposed and evaluated.

2. Accident profile

2.1. Project background

The water intake project is located on the bank of the Yangtze River. The construction element of this project included the water intake pipe, the gravity pipe, the launch shaft/working well, and the water pumping station. Two sets of steel pipes (#1 and #2) with an outer diameter (D) of 1.8 m, a thickness (t) of 20 mm, and a total length of 1656 m, were constructed by the pipe-jacking method. The depth of the working well was 43.5 m. The water intake bell-mouth is at a depth of 15 m in the Yangtze River.

The elevation of the ground surface where the working well is located is +6.50 m (the elevation of the Yangtze River surface is about +4.5 m). The elevations of the pipe center at the working well and at the pipe-jacking end are about −30.0 m and −47.50 m, respectively. Where crossing through the main channel of the Yangtze River, the gradient of the first 800 m of the total length is 15% downward. The gradient of sections 800–850 m, 850–1090 m, and 1090–1120 m are 14%, 13%, and 12%, respectively. The gradient of every 10 m in the section of 1120–1230 m decreases by 1%. Finally, the pipes are jacked horizontally from 1230 m to the required position.

2.2. Geological condition

According to the geological exploration report, the area is divided into six geological layers as shown in Table 1. The pipes successively cross 100 m of silty clay in layer 4-2, 400 m of silty clay in layer 5-2 and 1200 m of silt in layer 4-3 as it proceeds from the working well.

2.3. Background to the engineering accident

The project involved the construction of extra-long, curved steel pipes as shown in Fig. 2. The design jacking force is 8000 kN based on the material strength. Due to the buried depth and the pipeline passing through complex soil layers, the actual jacking force is much lower than 8000 kN. A comparatively high vertical deflection occurred in pipe #2, and a local buckling event happened at some sections in the pipe-jacking construction phase. Detailed information is presented as follows:

(1) When pipe #2 was jacked to 520 m cumulatively, there was a slight deflection on the steel pipe at a distance of about 280 m from the working well. The site engineers had conducted tracking measurements for 160 m from that point to the two ends, respectively. The inner diameter was 172.2 cm and the transverse width was 185.8 cm at the maximum deflection section, i.e., the maximum vertical compression was 7.8 cm and the maximum transverse extension was 5.8 cm. After nine days of tracking measurements, the vertical deflection reached the maximum value at a section 280 m away from the working well. The deflection then gradually decreased after passing this section. The inner diameter recovered to 174–175 cm. A small deflection occurred in the following pipes.

(2) When pipe-jacking reached 830 m cumulatively, the height of the pipe was 166.6 cm and the transverse width was 190.0 cm at the section of 410 m away from the working well, i.e., the vertical compression was 13.4 cm and the transverse extension was 10 cm. When pipe-jacking reached 870 m cumulatively, the height of the section recovered to about 173 cm.

(3) When pipe-jacking reached 870 m cumulatively and the jacking force was maintained at approximately 6600 kN, the bottom of the steel pipe deflected upwards suddenly at the section of 290 m from the working well. The length of the uplifted area was 7 m, and the width was 0.6 m. The maximum deflection of the pipe was over 50 cm, and its clear height was 123 cm, as shown in Fig. 3. The actual