Tunnelling and Underground Space Technology 49 (2015) 218–229

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Numerical simulation for the estimation the jacking force of pipe jacking

J. Yen, K. Shou *

Department of Civil Engineering, National Chung-Hsing University, Taichung, Taiwan

ARTICLE INFO

Article history:
Received 8 December 2014
Received in revised form 27 March 2015
Accepted 23 April 2015

Keywords:
Pipe jacking
Jacking force
Jacking force estimation
The displacement control method
FEM analysis
Soil–pipe interaction

ABSTRACT

For a pipe jacking construction, reducing the soil–pipe interface friction and providing enough jacking force are the most common approach to optimize the construction efficiency. In practice, jacking force is generally estimated by various empirical equations. However, the estimations of empirical equations frequently deviate from the reality. In this study, a model coupling finite element method and a displacement control method were applied to estimate the required jacking force in pipe jacking. Two cases were examined from Central Taiwan, where the primary geological foundation composed of gravel formations. Case A pertained to pipe jacking construction during which sewage pipes with a diameter of 2.4 m were utilized. The monitoring data from this case were used to establish the jacking force estimation model. The jacking force history observed in Case B, in which sewage pipes of 1.0 m diameter were used, was compared with those obtained by the developed model to demonstrate the applicability of the model. The results suggested the developed model can estimate the jacking force with a better accuracy towards the middle and the final stage of the pipe jacking process.

1. Introduction

In engineering design, numerical analysis is commonly applied to the simulation of engineering behavior. Through numerical simulation, the engineering behavior of soil–pipe interaction can be rapidly determined for use as the basis of a better engineering design. This is done by establishing the impact of the pipe jacking construction on buildings and pipelines adjacent to the pipe jacking route. Most of the studies adopt the force control method, in which the force boundary conditions are given (Barla, 2006, 2013; Broere, 2007; Shou et al., 2010; Shou and Yen, 2010; Li, 2012).

In the force control method, after the jacking force is obtained by using various empirical or theoretical equations, it is included as input data for the numerical model to simulate pipe jacking. If the jacking force is insufficient, the pipes cannot be jacked to the appropriate position. In contrast, the jacking force may be excessive, and causing penetration through the excavation face, in which modifications will be required to obtain the suitable jacking force. However, it will be required to carry out a trial-and-error modification to obtain a suitable jacking force value (Shou et al., 2010; Shou and Yen, 2010).

There have been numerous studies exploring and discussing the estimation of jacking force (Chapman and Ichioka, 1999; Staheli, 2006; Beckmann, 2007; Jiang, 2008; Röhner, 2010). During construction, the jacking force may be excessively large to overcome the excessive resistance, causing damage to the pipes, or overly small, resulting in inefficient or failed pipe jacking operations. Numerical simulation can be conducted before the actual pipe jacking construction to estimate the required jacking force employed in various construction conditions and jacking distances. The results of simulation can help construction workers in preparing lubricants and arranging intermediate jacking stations, in order to prevent pipes from being damaged by excessive jacking force, and to achieve the ultimate goal of improving pipe jacking efficiency.

In this study, the displacement control option in the numerical analysis software ABAQUS (Abaqus Inc., 2012) was used to designate the displacement at the end cross section of the pipe in the launch shaft. Accounting for the contact property and the contact range between the pipes and the soil during the jacking process, the stresses exerted on the pipes were used to back-calculate the jacking forces.

2. Lubrication and jacking force estimation models

In a pipe-jacking construction, the functions of lubrication include supporting the excavated face, reducing the radial effective stresses in the pipe, and conditioning the excavated soil into a dischargeable mixture. However, new chemical additives have been developed and applied. Their main purposes can be creating a

* Corresponding author. Tel.: +886 4 22850989 (O); fax: +886 4 22862857.
E-mail address: kjshou@dragon.nchu.edu.tw (K. Shou).

http://dx.doi.org/10.1016/j.tust.2015.04.018
0886-7798/

List of notations

γ_t	unit weight of the soil (kN/m^3)
φ	friction angle (°)
ϕ_r	residual friction angle of the soil (°)
μ'	frictional coefficient
μ_{int}	soil–pipe residual interface frictional coefficient
E	Young's Modulus (kN/m^2)
v	Poisson's ratio
D	the pipe outer diameter (m)
L	the length of pipe or the length of jacking (m)
r	radius of pipe (m)
c	cohesion of soil (kN/m^2)
C_a	cohesion between pipe and soil (kN/m^2)
τ_a	shear stress between pipe and soil (kN/m^2)
P_w	slurry pressure (kN/m^2)
σ'	earth pressure (kN/m^2)
fc'	the specified compressive strength (kN/m^2)
P_o	the face resistance
f_0	the primary resistance force in the excavation
P	the frictional resistance per unit area
K_0	coefficient of lateral pressure
F_0	initial resistance force (kN)
P_e	jacking force per unit area of excavation face (kN/m^2)
JF_{frict}	frictional component of jacking force (kN)

protective layer to repel surrounding water, reducing the permeability of the soil near the lubricant-soil boundary, etc. (Milligan and Norris, 1994; Milligan, 2000; Borghi, 2006).

There are various studies investigating the jacking force by theoretical derivations (Japan Micro Tunnelling Association, 2000; Pellet-Beaucour and Kastner, 2002; Chiang, 2006); by examining the mechanical behavior of soil, jacking force can be calculated while accounting for the overburden pressure on the pipes. However, due to the geological conditions and complicated construction scenarios, various pipe jacking techniques and lubricants were developed and applied. And it is quite difficult that the assumptions of those theoretical derivations match the real scenarios.

During pipe jacking work, annular gaps between the pipes and soil are incorporated into the engineering design which can reduce the soil–pipe interaction and the frictional resistance. Typically, the annular gaps, otherwise known as the overcut, are achieved by the copy cutters at the cutter head of the pipe jacking machine. However, the influence of the annular gap is either not considered or not clearly considered in the theoretical equations, and the values of jacking forces obtained from those theoretical equations are generally larger than the actual values measured. Hence, although the theoretical equations can be used to estimate the jacking force, they could not be directly applied to real pipe jacking operations.

Marshall (1998) proposed the stress measurements at the pipe–soil interface show that the relations between jacking loads, pipeline misalignment, stoppages, lubrication, and excavation method area highly complex. Pellet-Beaucour and Kastner (2002) pointed out that the frictional force is the main component of the resistance to pipe jacking, and the major controlling factors on friction are lubrication, stoppage, deviation and overcut. In recent years, various methods have been developed and discussed to improve jacking force estimation. Chapman and Ichioka(1999) and Staheli (2006) collected site monitoring data and focused on the identification of the mechanisms of soil–pipe and the development of jacking force prediction model. Chiang (2006) proposed a formula for the calculation of the friction generated in the pipe jacking construction process, and the dynamic friction value in accordance with the geological condition, in order to determine the possible maximum jacking length. Broere (2007) proposed a model to describe the movement of a microtunnelling machine as a combination of translational and rotational displacement, and tried to calculate the required steering jacks needed to obtain a desired boring curvature. In addition, the CoJack method (Stein, 2006; Beckmann, 2007), the improvements of the ATV A-161 method (Röhner, 2010), and the kinematic method of limit analysis theory (Li, 2012) can be collectively applied to calculate the allowable jacking force. However, it is essential to collect the monitoring data or obtain the parameters that influence the pipe jacking construction, such as geological conditions, material properties of both the pipe and the soil, the frictional coefficients of lubricants, pipe jacking methods, and down time during pipe jacking.

Shou et al. (2010) conducted testing to generate various frictional coefficients for lubricants used during pipe jacking construction and changed the range of contact between pipes and soil, obtaining parameters for the numerical analysis to simulate construction behavior and determine the interaction between pipes and soil. Barla (2013) used PFC2D to improve the applicability of the microtunnelling technique in the area of Torino, and presented methods to estimate the jacking force for microtunnelling. In the numerical simulation of pipe jacking, the jacking force value is generally calculated using empirical equations. However, a trial-and-error testing must be conducted to adjust the jacking force value, thereby producing the most appropriate value that jack the pipe to the designated distance. In this study, a jacking force estimation model was generated by using the displacement control numerical simulation. In this model, the displacement was imposed at the cross section of the pipe in the launch shaft, and the jacking force exerted on the pipe was calculated based on the obtained stress distribution.

The displacement control approach was used in the simulation of geotechnical problems, including the soil–structure interaction and the back analysis to obtain the material properties. The displacement of rock mass can be measured or designated to back calculate the parameters of the geostructures or to feed back the support design (Swoboda et al., 1999; Zhang et al., 2006; Yazdani et al., 2012). With the displacement control approach, Yu (2009) used finite element method to simulate the pulling-up processes of plate anchors. Cheng et al. (2007) and Dijkstra et al. (2011) used the displacement control numerical method to simulate the installation of pile foundation and predict the ground movements and deformations. Besides, Zhang et al. (2012) simulated the installation of the pipe roof support in tunneling; Hasanpour et al. (2014) simulated the shield tunneling, for preventing the penetration of rock mass into shield elements due to large displacements in squeezing grounds. In these studies, the method of displacement control was also applied to simulate the contact surfaces or the specified points. However, it is scarce that the displacement control approach was used in the estimation of jacking force in pipe jacking, which motivates this study.

3. Numerical analysis methods

3.1. Numerical models for the cases

The numerical software ABAQUS, a finite element software was used in this study. The analyses focused on two construction cases in the Taichung Science Park. The inner diameters of the pipes used