Geotechnical Aspects of Underground Construction in Soft Ground – Viggiani (ed)
© 2012 Taylor & Francis Group, London, ISBN 978-0-415-68367-8

Influence of overcut length on jack force and acting earth pressure during pipe jacking

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ABSTRACT: Pipe jacking method pushes a tunnelling machine through concrete pipes ahead of the jacks. The main factors influencing jack force is the friction resistance between pipes and ground. To reduce the resistance, the overcutting between pipes and the surrounding soil is carried out. So far, most of the analytical or empirical models estimating jack force do not consider the overcutting area, then the pipe behavior is not still clarified well. To overcome this problem, the new analysis model, called as the stack pipe model, has been developed by using the full ground spring model that can take overcutting effect into consideration. This study aims to make clear the influence of the overcut length on jack force and earth pressure acting on pipes by parameter studies. As a result, it was found that jack force and acting earth pressure on pipes are greatly influenced by the overcut length.

1 INTRODUCTION

Pipe jacking method is an economically rational and environmentally safe technique for installing underground pipelines. Hydraulic jacks are used to push pipes and TBM through the ground from a launching shaft at the same time as excavation is taking place with the TBM. The main factor influencing jack force is the frictional resistance between pipes and ground. To reduce the friction resistance, the excavation radius by a TBM is larger than the outer radius of the pipes, that is, the over-cutting area between pipes and ground exists, which is a significant factor giving influence to jack force.

It is important to calculate the jack force accurately to design a jacking pipe safely and economically. Prediction models on jack force based on some analytical and empirical approaches were proposed (Atalah et al. 1994; Japan Sewage Association 2000; Phelipot et al. 2001). However, most of the models estimating jack force do not consider the over-cutting area, then the pipe behavior is not still clarified. To overcome this problem, the new analysis model, called as the stack pipe model, has been developed by using the full ground spring model that can take over-cutting into consideration (Sugimoto & Asanprakit 2010). This analysis model has been validated using ideal data and site measured data in the previous research.

The main objective of this paper is to make clear the influence of the overcut length on jack force and earth pressure acting on pipes by parameter studies using the above-mentioned stack pipe model. Subsequently, the simulation results are examined from the viewpoint of geometric conditions and mechanics. Finally, the influence of overcut length on jack force and pipe behavior is discussed.

2 STACK PIPE MODEL

2.1 *FEM analysis model*

The FEM software package DIANA was used for the analysis. The pipe surface was modeled by a four-node quadrilateral isoparametric curved shell element. A total of 32 divisions and eight divisions were generated in a circular and an axial direction, respectively, to configure a pipe shape. The ground was represented by 2-node translation spring elements called "ground spring", which is attached perpendicularly to the pipe axis between each node of the pipe surface and initial excavation surface. Moreover, the cushion material inserted between the pipes and the machine connection between the pipe and machine were also modeled by 2-node translation spring elements in the axial, radial, and tangential directions. The former and later spring elements are called "joint spring" and "machine connection spring", respectively. The frictional resistance around the pipe during jacking is a dynamic friction, and it does not depend on the relative displacement in the axial direction between the pipe and the ground. The friction between the pipe and the ground was accomplished by a Mohr-Coulomb friction interface element. Fig. 1 shows a FEM model for pipe jacking analysis, where L is the absolute pipe length and t_a is the cushion thickness.

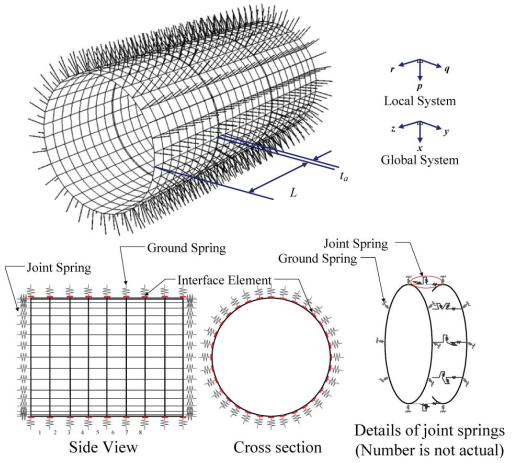
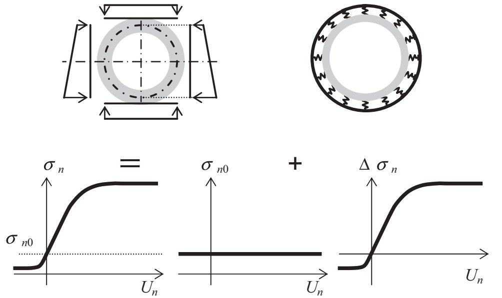


Figure 1. 3D finite element model.



(a) ground reaction curve (b) initial earth pressure (c) earth pressure change

Figure 2. Interaction model between ground and pipe.

2.2 *Ground spring model*

In the ground spring, the ground reaction curve shown in Fig. 2 was adopted as the interaction model between the ground and the pipe. In the figure, U_n is the length of the perpendicular line from the initial excavation surface to the pipe surface (+: outward), and σ_n is the normal earth pressure acting on the pipe. σ_n is composed of the constant initial earth pressure due to overburden load σ_{n0}, and the earth pressure change $\Delta\sigma_n$, which depends on U_n. In the analysis, σ_{n0} is introduced by a pre-stress force in the ground spring before analysis. $\Delta\sigma_n$ is generated as a result of the analysis. In addition, σ_n is the total earth pressure for the Total Stress Analysis, and the effective earth pressure for the Effective Stress Analysis. By using this ground spring model, it is not necessary to carry out an initial stress analysis as a general finite element analysis. Furthermore, a rigid body displacement of the pipe in the transverse direction can be allowed.

The nonlinear ground reaction curve developed in the kinematic shield model (Sugimoto & Sramoon 2002), as shown in Fig. 3, was adopted to represent the ground reaction curve in Fig. 2(a). The relationship of the coefficient of earth pressure in the vertical and horizontal directions, K_v and K_h, and the distance from the initial tunnel surface to the pipe, U_n, (+: outward of tunnel) can be represented by

$$K_h(U_n) = \begin{cases} (K_{h0}-K_{h\min})\tanh\left(\dfrac{a_h U_n}{K_{h0}-K_{h\min}}\right)+K_{h0} & (for\ U_n \le 0) \\ (K_{h0}-K_{h\max})\tanh\left(\dfrac{a_h U_n}{K_{h0}-K_{h\max}}\right)+K_{h0} & (for\ U_n \ge 0) \end{cases} \tag{1}$$

$$K_v(U_n) = \begin{cases} (K_{v0}-K_{v\min})\tanh\left(\dfrac{a_v U_n}{K_{v0}-K_{v\min}}\right)+K_{v0} & (\text{for } U_n \le 0) \\ (K_{v0}-K_{v\max})\tanh\left(\dfrac{a_v U_n}{K_{v0}-K_{v\max}}\right)+K_{v0} & (\text{for } U_n \ge 0) \end{cases} \tag{2}$$

where K_{h0} is the coefficient of earth pressure at rest; K_{v0} is the initial coefficient of vertical earth pressure normally equal to 1; subscripts max and min indicate the upper and lower limit of the coefficient of earth pressure, respectively; and a_h and a_v are the gradient slope of function K_h and K_v at $U_n = 0$, respectively. Moreover, the coefficient of earth pressure in any direction, K_θ, can be interpolated as

$$K_\theta(U_n,\theta) = K_v(U_n)\cos^2\theta + K_h(U_n)\sin^2\theta \tag{3}$$

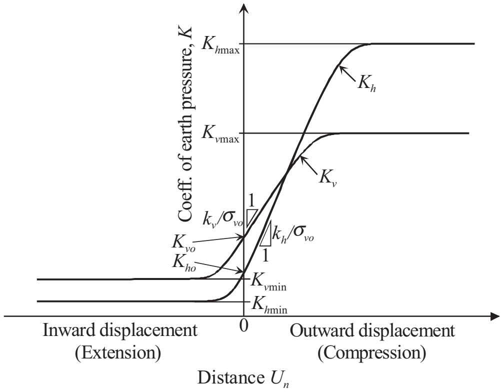


Figure 3. Ground reaction curve.

where θ is the angle from the downward vertical direction. Finally, the earth pressure normal to pipe surface, σ_n, can be estimated from

$$\sigma_n = K_\theta(U_n, \theta)\sigma_{v0} \tag{4}$$

3 ANALYSIS CONDITIONS

In this study, three analysis cases with changed overcut length of 0.005, 0.010, 0.015 m, respectively, were adopted to examine the pipeline behavior.

All analysis cases were carried out in a single layer of sandy ground, which total unit weight is 20 kN/m^3 and the groundwater level is 0.50 m below the ground surface, as shown in Fig. 4. As shown in Fig. 5, the tunnel is 20.12 m long, which is composed of the straight alignment and a rightward curved alignment with a radius of 50 m. The beginning point of curve (*BC*) and the end point of curve (*EC*) are located at the distance of 75.63 m and 84.35 m, respectively. The coefficient of vertical subgrade reaction k_v was assumed to be equal to k_h. Table 1 shows the detailed values for the tunnel, pipe, and ground properties.

The cushion material and the watertight rubber ring are placed within the collar of the pipe. The characteristics of the joint spring in the axial direction and radial and circumferential directions were set by the cushion material specification (Sekisui Plastic Co., Ltd. 2004), as shown in Fig. 6 and Table 2.

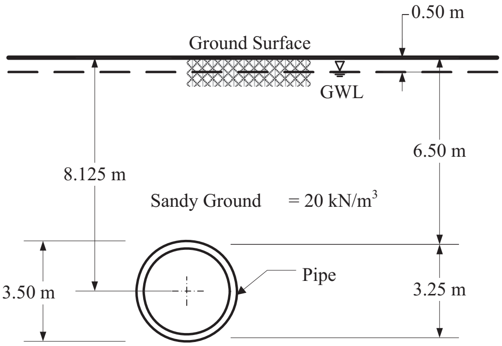


Figure 4. Geological profile.

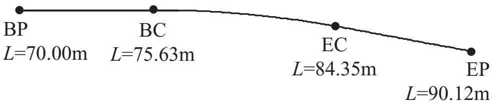


Figure 5. Horizontal alignment.

Table 1. Analysis conditions.

Item	Parameter	Value
Tunnel	Horizontal curve radius (rightward)	50 m
	Rotation angle of the curve	10 degree
	Vertical slope gradient	0.0%
	Tunnelling depth	6.50 m
	Groundwater level	0.50 m
	Overcut length	0.005, 0.010, 0.015 m
Pipe	Inner radius of pipe	1.500 m
	Length of pipe	0.80 m
	Pipe thickness	0.25 m
	Cushion thickness	0.04 m
	Class of cushion material	FJ2.0
	Cushion position	90 degree
	Young's Modulus of pipe	3.6×10^7 kN/m^2
	Poisson ratio	0.17
	Concrete density	24 kN/m^3
Ground	Effective Overburden Pressure at spring line	86.25 kPa
	Hydrostatic pressure at spring line	76.25 kPa
	Dynamic friction coefficient	0.1
	Dynamic adhesion	0.0 kN/m^2
	Coeff. of earth pressure $K_{h\min}$	0.01
	K_{h0}	0.50
	$K_{h\max}$	5.00
	$K_{v\min}$	0.01
	K_{v0}	1.00
	$K_{v\max}$	5.00
	Coeff. of subgrade reaction k_h	15000 kN/m^3
	k_v	15000 kN/m^3

Table 2. Spring constant of joint spring.

Direction	Disp. (m)	Spring constant (kN/m/each)
Axial dir. with cushion		4222500
	–0.020	242679
	–0.016	72589
	–0.012	31107
	–0.004	124464
	–0.002	580750
	0.000	0.71
Axial dir. without cushion		7.143E + 06
	–0.040	0.71
Radial, circumferential dir.		3.125E + 06
	–0.045	2.792E + 05
	0.045	3.125E + 06

The stiffness constant in the radial direction of the interface element was set so that 1 mm relative displacement generates 100 MPa stress to fix the ground spring on the pipe surface. The stiffness constant in the tangential direction of the

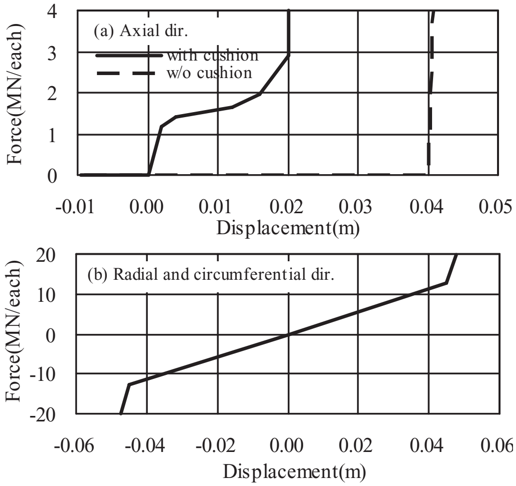


Figure 6. Characteristics of joint spring.

Table 3. Properties of the interface element.

Properties	Value
Stiffness constant in normal dir. (kN/m^3)	1.00E + 08
Stiffness constant in tangential dir. (kN/m^3)	3333
Frictional constant	0.1
Adhesion (kN/m^2)	0.0

Table 4. Spring constant of the machine connection spring.

Direction	Properties	Value
Axial dir.	Spring constant (kN/m)	3005.61
	Pre-stress force for all (kN)	1017.43
Radial dir.	Spring constant (kN/m)	1.0
Circumferential dir.	Spring constant (kN/m)	1.0

interface element was set to be equivalent to the tangential spring with 1/3 spring constant of the ground spring (Railway Technical Research Institute 1997). Table 3 shows the properties of the interface element.

Usually, the face pressure is on the compressive side from the earth pressure at rest. Then the spring constant of the machine connection springs in the axial direction was set, as shown in Table 4, taking account of the ground properties and the number of machine connection springs.

4 SIMULATION RESULTS

By changing the overcut length U_{n0} among 0.005, 0.010, and 0.015 m, the contour maps of the gap from the initial tunnel surface to the pipe periphery U_n (+: outward of tunnel) and the normal earth pressure σ_n around the pipe periphery during jacking are shown in Fig. 7 and Fig. 8, respectively. Note that the pipe periphery is unfolded as a flat plate, that is, the vertical axis shows the circumference of the pipe, while the horizontal axis shows the distance. The vertical lines in both figures represent the end of each pipe. In addition, the jack force is shown in Table 5.

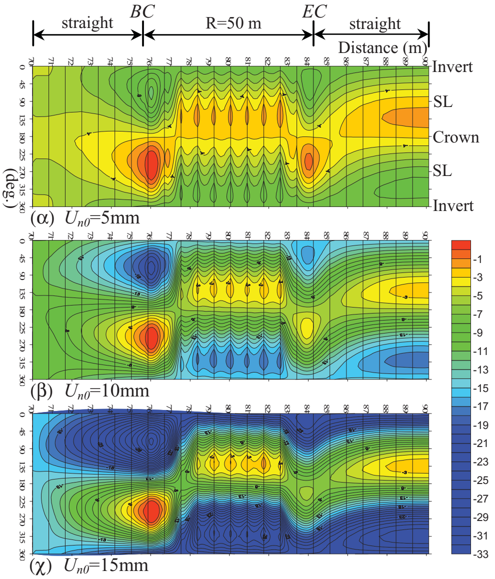


Figure 7. U_n distribution around pipe (mm).

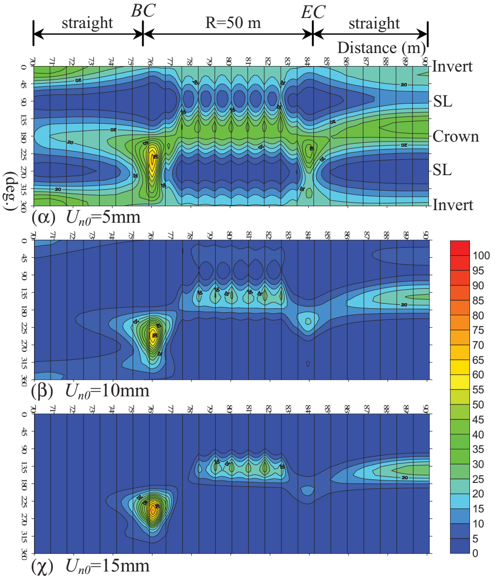


Figure 8. σ_n distribution around pipe (kN/m^2).

Table 5. Jack force and resistance.

Overcut length m	Jack force F_J kN	Resistance at face F_f kN	Resistance around pipe periphery F_R kN	F_R/L kN/m	F_R/A kN/m^2
0.005	1457	1143	314	16.37	1.60
0.010	1265	1145	120	6.25	0.61
0.015	1227	1148	79	4.13	0.40

From Fig. 7 and Fig. 8, the followings are found:

1. U_n has a negative sign in the whole area due to the over excavation.
2. Along the pipeline, U_n on the top is larger than U_n at the bottom. It means that the pipeline moves upward to the tunnel crown due to the over excavation and the buoyancy force.
3. At the rear end of the first pipe, U_n is close to the values of over excavation due to the fixed boundary condition in the transverse direction.
4. U_n is larger at the left spring line along the straight and curved alignments and at the right spring line around *BC* and *EC*. These come from the bending stiffness at the joint due to the cushion material and the magnitude of the jack force. This behavior is reasonable from the viewpoint of geometric condition.
5. On the curved alignment, U_n is larger at both ends of the pipe on the convex side and at the center of the pipe on the concave side. This is also reasonable from the viewpoint of geometric conditions.
6. σ_n at the top and bottom is larger than σ_n at the spring line. This results from $K_{h0} = 0.5$.
7. σ_n distribution agrees with the U_n distribution. σ_n is less than the initial overburden pressure σ_{n0} because of $U_n < 0$.

Comparing the results in Fig. 6, Fig. 7 and Table 5, the influence of overcut length U_{n0} are found as follows:

1. The larger the overcut length U_{n0} is, the larger U_n at the top is. At the same time, U_n at other positions become smaller. This comes from that the pipeline was moved upward due to the buoyancy force when U_{n0} increased. Relatively U_n at other positions decreased due to geometric conditions.
2. With the increase of the overcut length U_{n0}, the area of earth pressure which closed to 0 increased, too.
3. The jack force F_J and the friction resistance F_J around pipe decrease with the increase of the overcut length U_{n0}. This is because the over cutting significantly reduces the contact between pipe and ground.

5 CONCLUSIONS

The parametric study focused on overcut length was carried out using the stack pipe model. The simulation results were examined from the viewpoint of geometric conditions and mechanics. As a result, it was confirmed that the proposed analysis model can express the gap between initial excavated surface and pipes, the earth pressure acting on pipe surface, the jack force, and the frictional resistance around pipe surface reasonably. In addition, it was found that jack force and acting earth pressure on pipes are greatly influenced by the overcut length.

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