A study of jacking force for a curved pipejacking

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Abstract: For a pipejacking, the jacking force is critical to balance the resistance force and to move the pipe string forwards. The driving mechanism of a curved pipejacking is more complicated than a straight-line pipejacking, and its jacking force is also more difficult to be determined. The paper theoretically studies the jacking force of a curved pipejacking by considering the static equilibrium of earth pressure, resistance at cutting face, friction at pipe surface, and the driving force behind the pipe string. The derived theoretical formula can be used to estimate the driving forces of a straight-line or a curved pipejacking. Case study was performed by applying the theoretical and empirical formulae. After calibration, the corrected formula is more accurate and more applicable.

Key words: pipejacking; curved pipejacking; jacking force; statics analysis

1 Introduction

In modern urban areas, constructing underground pipelines is a challenge. Traditional cut and cover method not only creates grid-locked traffic and noise pollution, but also hampers commercial activities. Overall, cut and cover method has to pay more and more social costs. In response to these shortcomings, many alternative no-dig construction methods have been developed.

Use of no-dig construction methods might still have difficulties in developed urban centers, with obstacles such as intersections, narrow winding roads, and existing underground utilities. It is possible that in many situations, intermediate shafts cannot be excavated. The feasible solutions are to establish working shafts away from impact points, and use curved pipejacking methods.

For a pipejacking, the pipes could be damaged by stress concentration due to unbalanced or excessive jacking forces, resulting in the difficulty of pipejacking. Comparatively speaking, the driving mechanism of a curved pipejacking is more complicated, and its driving force is also more difficult to be determined. This study uses the theory of static equilibrium to derive a jacking force formula for a curved pipejacking.

2 Review of related studies

Generally, specific simplified assumptions must be made to analyze the mechanical behavior of a pipejacking. For example, it could be assumed that materials are isotropic, homogeneous, and possess linear-elastic characteristics; the next step involves quantitative analysis and deriving methods to find solutions. Unfortunately, these assumptions deviate from real problems to some extent as to whether or not data from theoretical assessment are applicable. On the other hand, many researchers have introduced empirical formulae for application in project planning.

Nanno [1] examined the forces generated during curved jacking and the problems encountered during construction, and concluded that a V-shaped gap existed between each pipe in curved sections. As a result, the eccentric thrust between each pipe was transmitted by the V-shaped end-points. And the force system was derived from the eccentric thrust. Wei et al. [2] analyzed the path offset during straight-line and curved jacking, and proposed that pipes experienced two extreme states of stress: the first occurred when jacking force was eccentrically distributed on the same side of the pipes; the second occurred when jacking force was distributed on both sides of the pipes. Due to geometric relationships involved in curved pipejacking, jacking force transmission between pipe sections occurs on the inner side, producing an eccentric...
jacking. As there is a deviation angle between the two adjacent pipes, outward-directed force components that produce a rotational moment are created.

Broere et al. [3] examined the force and motion of TBM involved in excavating curved tunnels in soil. The research of Broere et al. suggested that the motion of TBM during the curved jacking included components of displacement and rotation. And they went on to examine a curved jacking of a curved double-shield TBM, and hypothesized a force equilibrium graph of TBM while digging, thereby derived a shift moment formula. A shift moment of 0 suggests that the TBM experiences only a shift motion, but does not rotate, while a shift moment more than 0 suggests that the TBM rotates as well.

Chen [4] used static equilibrium to analyze the forces acting on pipes in a curved pipejacking, and examined the relationship between lateral earth pressure, surface resistance of cutting face, and total jacking force when pipes were jacked along a specific path. Chen’s analysis was divided into three parts: first pipe segment, intermediate pipe segments and terminal pipe segment. Chen’s research assumed that the sandy soil possesses homogeneous and isotropic properties. Unlike the assumption of Chen [4], this study considers that the distribution of the induced lateral external earth pressure of adjacent pipes is discontinuous. The external force transmitted from the adjacent pipe segment is limited to the jacking force only. In jacking force analysis and derivation, the resistance at cutting face is used to calculate total jacking thrust by a direct calculation; total jacking thrust can also be used to calculate the resistance at cutting face by an inverse calculation. The lateral earth pressure for each pipe segment is identical for the above direct calculation and inverse calculation. Although the formula is based on the direct calculation, the inverse calculation can apply the same formula by switching the unknown and the known.

3 Theoretical derivation of jacking force

In this study, a curved pipejacking is analyzed separately for the first pipe segment, intermediate pipe segment, and the terminal pipe segment. Except the first and terminal pipes that directly connect to straight-line pipe segments, the pipes in the curved section can apply the intermediate pipe analysis. This study assumes that the sandy soil possesses homogeneous and isotropic properties. Unlike the assumption of Chen [4], this study considers that the distribution of the induced lateral external earth pressure of adjacent pipes is discontinuous. The external force transmitted from the adjacent pipe segment is limited to the jacking force only. In jacking force analysis and derivation, the resistance at cutting face is used to calculate total jacking thrust by a direct calculation; total jacking thrust can also be used to calculate the resistance at cutting face by an inverse calculation. The lateral earth pressure for each pipe segment is identical for the above direct calculation and inverse calculation. Although the formula is based on the direct calculation, the inverse calculation can apply the same formula by switching the unknown and the known.

3.1 Analysis of the first pipe segment

Figures 1 and 2 illustrate the detailed top view and the cross-section of the forces acting on the first pipe segment, respectively. The major variables are jacking force $T_1$, induced earth pressures, $\sigma_{1.1}$ and $\sigma_{2.1}$, to maintain the equilibrium. It is worth noting that the lengths $l_1$ and $l_2$ in Fig.1 are defined according to the transition from $\sigma_{1.1}$ to $\sigma_{2.1}$. In other words, $l_1 = \sigma_{1.1} L_1 / (\sigma_{1.1} + \sigma_{2.1})$ and $l_2 = \sigma_{2.1} L_2 / (\sigma_{1.1} + \sigma_{2.1})$.

![Fig.1 Top view of the force system of the first pipe segment.](image1)

![Fig.2 Cross-section of the force system of the first pipe segment.](image2)
\[ l_2 = \frac{\sigma_{z,1} L_1}{(\sigma_{z,1} + \sigma_{z,2})}, \] where \( L_1 \) is the length of the first pipe segment.

This study examines the pipe jacking force only in the horizontal direction. Pipe surface is considered and calculated as described below. Integration method is used to obtain the total surface loads at different locations. For simplicity, this study assumes that the top direction of the pipe is 0° and the angle increases in a clockwise way. The range of the outside surface area of the curved segment is between 0° and 180°, and the range of inner surface area is between 180° and 360°.

The primary external forces acting on each pipe segment include: (1) jacking force; (2) jacking resistance force; (3) force from the static lateral earth pressure; (4) force from the earth pressure to maintain the equilibrium; and (5) frictional resistance produced by contact between the soil and the pipe.

The resistance force on the first segment refers to surface resistance at cutting face. However, for other segments, jacking resistance refers to the jacking force of the former segment. The static earth pressure does not vary among pipe segments, and its resultant force on the pipe is consistent. The resultant force acts on the pipe symmetrically and has no impact on the static equilibrium of the pipes. However, the friction produced by the static lateral earth pressure has an impact on the equilibrium, therefore, it is necessary to calculate the resultant force of the lateral earth pressure.

The static earth pressure includes the vertical earth pressure at the top, \( \sigma_v \) (kPa), the vertical earth pressure at the bottom, \( \sigma'_v \) (kPa), and the horizontal earth pressure at both sides, \( \sigma_h \) (kPa). The formulae can be expressed as:

\[
\begin{align*}
\sigma_v &= \gamma H \\
\sigma'_v &= \gamma (H + d) \\
\sigma_h &= \gamma \left( H + \frac{d}{2} \right) K_0 \\
K_0 &= 1 - \sin \phi'
\end{align*}
\]

where \( \gamma \) is the unit weight of the soil (kN/m³), \( H \) is the depth from the ground surface to the top of the pipe (m), \( d \) is the diameter of the pipe (m), \( K_0 \) is the lateral earth pressure coefficient, and \( \phi' \) is the internal friction angle of soil (°). The resultant force of the static earth pressure is subjected to the forces resulting from the above earth pressures acting on the pipe surfaces.

3.1.1 Force equilibrium in x-direction

External forces for the force equilibrium formula in x-direction include: x-direction component of the jacking force, the force resulting from the static earth pressures, and the earth pressures induced to maintain the equilibrium. The formula is derived by performing static equilibrium analysis of these external forces:

\[
\sum F_x = (x\text{-direction component of reaction force } T_i) + (\text{resultant force of earth pressure on inner side}) - (\text{resultant force of earth pressure on outer side}) = 0
\]

The distributions of the earth pressures are shown in Fig.3.

3.1.2 Force equilibrium in y-direction

External forces for the force equilibrium formula in y-direction include: y-direction component of the jacking force, the resultant forces of friction produced by the static earth pressure and by the induced earth pressure (to maintain the equilibrium), respectively, and the friction produced by the weight of pipe. These
external forces are used for static equilibrium analysis to derive the following formula:

$$\sum F_y = (\text{resultant force } P_y) + (\text{resultant force of friction on outer side}) + (\text{resultant force of friction on inner side}) + (\text{friction produced by weight of pipe}) - (\text{y-direction component of resultant force } T_i) = 0 \quad (6)$$

Therefore, the resultant forces of the earth pressure on inner and outer sides can be obtained by integrating the static earth pressure and the reaction lateral earth pressure; the final formula can also be expressed as a function of the static earth pressure components $\sigma_y$, $\sigma_y'$, $\sigma_h$, the unknown reaction force $T_i$ and the unknown reaction lateral earth pressure components $\sigma_{1,y}$ and $\sigma_{2,y}$.

### 3.1.3 Moment taken in z-direction at point A

If the pipe does not rotate, the moment at any point of the pipe should be 0. For simplicity, this study considers moment in z-direction at point A (point A is located at the corner of the pipe), and derives the moment equilibrium formula by making the clockwise moment being equal to the counterclockwise moment:

$$\sum M_{z} = (\text{counterclockwise moment}) - (\text{clockwise moment}) = (\text{moment produced by } T_i + \text{moment produced by } P_n + \text{moment produced by } P_{2,1} + \text{moment produced by friction } P_{in,1} + \text{moment produced by friction } P_{2,1} + \text{moment produced by friction } P_{out,1} + \text{moment produced by friction } P_{1,1} + \text{moment produced by weight induced friction } F_{in,1}) = 0 \quad (7)$$

In summary, the above formulae can be used to calculate the following three unknowns: (reaction force variables) jacking force $T_i$, induced earth pressures to maintain the equilibrium, $\sigma_{1,y}$ and $\sigma_{2,y}$.

### 3.2 Analysis of the intermediate pipe segment

Figure 4 shows the top view of the force system of the intermediate pipe segment $(m = 2, 3, \cdots, n-1)$. Similarly, the static equilibrium formulae can be derived as follows.

(1) **Force equilibrium in x-direction**

$$\sum F_x = (x\text{-direction component of reaction force } T_{n-1}) + (\text{resultant force of earth pressure on inner side}) - (\text{resultant force of earth pressure on outer side}) = 0 \quad (8)$$

(2) **Force equilibrium in y-direction**

$$\sum F_y = (y\text{-direction component of } T_{n-1}) + (\text{resultant force of friction on outer side}) + (\text{resultant force of friction on inner side}) + (\text{friction produced by weight of pipe}) - (y\text{-direction component of } T_{n-1}) = 0 \quad (9)$$

(3) **Moment taken in z-direction at point A**

$$\sum M_{z} = (\text{counterclockwise moment}) - (\text{clockwise moment}) = (\text{moment produced by } T_{n-1} + \text{moment produced by } P_{in,n} + \text{moment produced by friction } P_{in,n} + \text{moment produced by friction } P_{2,n} + \text{moment produced by friction } P_{out,n} + \text{moment produced by friction } P_{1,n} + \text{moment produced by weight induced friction } F_{in,n}) = 0 \quad (10)$$

Similarly, Eqs.(8)–(10) can be used to calculate the three unknown reaction force variables: jacking force $T_{n}$, induced earth pressure to maintain equilibrium, $\sigma_{in,n}$ and $\sigma_{2,n}$. The solutions of the first pipe segment $T_{n-1}$, $T_{n}$ for $T_{n-1}$ and $m = 2$ are introduced to obtain the solution for the second pipe segment, so that the force is transmitted from the first pipe segment to the second one. Similarly, the solutions of the other intermediate pipe segments $(m = 2, 3, \cdots, n-1)$ can be subsequently solved, and the forces can be transmitted from the second pipe segment to the $(n-1)$-th pipe.

### 3.3 Analysis of the terminal pipe segment

Figure 5 shows the detailed top view of the force system of the terminal pipe segment (the $n$-th pipe), and the static equilibrium formulae are described as follows.

![Fig.5 Top view of the force system of the terminal pipe segment.](image-url)
(2) Force equilibrium in y-direction
\[ \sum F_y = (\text{y-direction component of } T_{1,0}) + (\text{resultant force of friction on outer side}) + (\text{resultant force of friction on inner side}) + (\text{friction produced by weight of pipe}) - T_{1,0} = 0 \] (12)

(3) Moment in z-direction at point A
\[ \sum M_{A_z} = (\text{counterclockwise moment}) - (\text{clockwise moment}) = (\text{moment produced by } T_{1,0} + \text{moment produced by } P_{1,0} + \text{moment produced by } P_{2,0} + \text{moment produced by friction } P_{1,a} + \text{moment produced by friction } P_{2,a} + \text{moment produced by friction } P_{o,0} + \text{moment produced by weight induced friction } F_{p,u,0}) = 0 \] (13)

Similarly, the above three equations can be used to solve the three unknown reaction variables: the jacking force \( T_{1,0} \), the induced earth pressures to maintain the equilibrium \( \sigma_{1,0} \), and \( \sigma_{2,0} \). The solution for the \((n-1)\)-th pipe segment can be introduced to find the solution of the \(n\)-th segment.

This study uses the software Mathematica to subsequently obtain the analytical solutions of each pipe, and then implements the solutions to a FORTRAN program for further applications. The established numerical program can be used to calculate the jacking force under different curved jacking conditions. Besides, it can also inversely back calculate the reaction at the cutting face from the jacking force at the other end.

4 Case study and calibration

A pipejacking project in Chiayi City, Taiwan, was adopted for a case study. The study included jacking force calculation by the derived theoretical formulae and other empirical formulae, and calibration coefficient calculation for the theoretical formula. The straight-line and curved pipe sections were 1.5 m in length, 2 m in outer diameter, 1.65 m in inner diameter, and curvature radius of 50 m. Both the straight-line and curved sections were considered to have five pipe segments.

The formulae introduced by Osumi [5] were used to compare the jacking force calculations. The formulae were only applicable to frictional resistance of the straight-line section, therefore, it was necessary to use other methods in conjunction to calculate the surface resistance of cutting face. This study also selects the empirical formulae proposed by the Japan Micro Tunneling Association (JMTA) [6] for jacking force calculations. Existing empirical formulae and derived theoretical formulae were compared to obtain the calibration coefficients.

As to the calculation of the surface resistance of cutting face, Staheli [7] summarized that researchers had different empirical jacking force formulae, but those formulae suggested that the shear plane ahead of the cutter head was subjected to a pressure between the active and the passive earth pressures. The actual force at the cutting face depends on the pipejacking machine and methods, also relates to the advancing rate and debris removing condition. In many cases, we must accelerate the advancing rate to enhance the progress, which in turn causes the pressure at the cutting face approaching the active earth pressure. Therefore, this study conservatively assumes that the pressure at the cutting face is equal to the active earth pressure.

The empirical jacking force formula must be applied in conjunction with other formulae to modify the straight-line pipejacking formula so that it can be applied to the curved pipejacking. This study utilizes the curved pipejacking formula proposed by the JMTA to modify the other straight-line jacking force formulae. Most empirical jacking force formulae involve the use of basic derivation, combining with case comparisons or reductions to maintain the consistency of jacking force during actual pipejacking construction. The theoretical formulae derived in this paper have not been corrected according to the real conditions in constriction. For example, the actual pipejacking always involves overcut rather than full contact between soil and pipe. This is one of the reasons for the overestimation of frictional resistance and jacking force by the theoretical formulae.

This study adopts different friction coefficients for simulation. According to the typical lubrication conditions, the friction coefficient \( \mu \) is considered to be 0.1, 0.129, 0.176 \( \frac{3}{2} \), 0.4 and 0.523. According to the suggestion of Scherle (1977) [7], the friction coefficient with lubrication is between 0.1 and 0.3. It is generally accepted that the frictional angle between pipe and soil is 1/2–1/3 of the internal frictional angle of the soil. If the internal frictional angle is 30°, the friction coefficient of the interface would be approximately 0.176 \( \frac{3}{2} \) (tan10°). Shou et al. [8] suggested that friction coefficients differed from the lubricants used. The friction coefficient is about 0.129 for...
plasticizers plus polymers, about 0.4 for bentonite, and about 0.523 for the condition without lubrication in the gravel formations of Central Taiwan. Five friction coefficients are used in conjunction with various empirical formulae to calculate the jacking forces. The results of the straight-line and the curved section are shown in Tables 1 and 2, respectively. The results show that the discrepancies exist between the results from different formulae and the setting of different parameters.

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<td>365.70</td>
<td>170.316</td>
<td>171.316</td>
<td>1 277.373</td>
<td>1 643.073</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Theoretical</td>
<td>0.24</td>
<td>365.70</td>
<td>709.652</td>
<td>710.652</td>
<td>5 322.387</td>
<td>5 888.087</td>
<td>—</td>
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<tr>
<td>JMTA</td>
<td>0.523</td>
<td>365.70</td>
<td>251.432</td>
<td>252.432</td>
<td>1 885.737</td>
<td>2 251.437</td>
<td>—</td>
<td></td>
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<tr>
<td>Theoretical</td>
<td>0.24</td>
<td>365.70</td>
<td>805.704</td>
<td>805.704</td>
<td>8 424.404</td>
<td>8 890.404</td>
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</tr>
</tbody>
</table>
Since different empirical formulae may have various degrees of correction or reduction, the proportion of friction might not be consistent with that of the friction coefficient. As a result, the calibration coefficients of the theoretical formulae in this paper differ from the friction coefficient. The relationship between the frictional calibration coefficient and the friction coefficient is shown in Fig.6. The frictional calibration coefficient falls between 0.234 and 0.459, indicating that, for high friction coefficients, the theoretical formulae will overestimate the jacking force. Therefore, corrections are necessary for the theoretical formulae.

In the simulation of the curved section, the theoretical formulae was verified by the Osumi and JMTA empirical formulae. The corrected frictional resistance formula was also included for a comparison (see Table 2). This paper uses the empirical formulae of JMTA to calculate the jacking force in the curved section. The results show that the frictional force from the theoretical formulae is greater than that from empirical formulae. Increases in the friction coefficients lead to unreasonable increases in the frictional resistance, indicating that the assumed parameters are inappropriate under high friction coefficients, and the formulae are unsuitable for high friction situations. However, under high friction coefficients, the additional moment caused by friction is much greater than that induced by the eccentric jacking force. This results in a high lateral earth pressure and an additional friction.

5 Conclusions and suggestions

This study studies the theoretical derivation of jacking force for curved pipejacking. It can estimate the jacking force for both straight-line section as well as curved section. The theoretical formulae overestimate the jacking force due to the unrealistic ideal assumptions; however, the corrected formulae can make a proper estimation.

The major source of error for curved segment could come from the additional unknown eccentric distance of jacking force. In statics, the force system is actually an unstable one, and the lack of one formula means that the solution cannot be directly found. Another equation must be introduced to solve this unknown variable. Otherwise, we can exclude one of the other unknowns by simplification to include the eccentric distance as an unknown. Future studies are suggested to include more scenarios to make the theoretical formulae more applicable and more robust.

References