CALCULATION METHODS THE JACKING FORCE IN PIPE JACKING TECHNOLOGY

*Le Hong Chuong[1]**

Abstract: *Jacking force is the most crucial factor in pipe jacking engineering. The calculation of jacking force directly affects to design of back wall pipe strength and intermediate jacking station. Especially in long distance pipe jacking construction, jacking force may decide the number and positions of intermediate jacking stations... The process of estimating the required jacking force to jack a pipe through the ground demands much experience and exacting judgment. There are many factors and risks affect to the determination of the jacking force that the engineers must care. In recent years, the pipe jacking technology is applied more and more for underground pipeline construction in Vietnam, especially in the big urban. This paper introduces and compares some agreeable methods which are being used in the world for estimating the required jacking force.*

Keywords: *Jacking force, Penetration resistance, Frictional resistance, Pipeline.*

Received: September 20th, 2017; revised: October 27th, 2017; accepted: November 2nd, 2017

1. Introduction

Microtunnelling, or Pipe Jacking Method, is a trenchless solution for constructing small diameter tunnels, used especially for projects that require the tunnel to cross under dense traffic roads, railways, rivers, etc. Microtunneling is a process that uses a remotely controlled Micro Tunnel Boring Machine (MTBM) combined with pipe jacking technique to directly install product pipelines underground in a single pass. Microtunneling is a closed-face pipe jacking operation where positive face stabilization is provided to the excavation by pressurized slurry. This feature allows tunneling below ground water or in unstable soil conditions without risk of soil settlement, soil heave, or loss of stability. The jacking pipe is pushed behind thrust boring machine from a starting shaft or launch shaft by the main jacking station located in drive shaft up to the target shaft or reception shaft. At the same time an unmanned, remote controlled microtunneling machine carries out the excavation at the tunnel face, the excavated material to be transferred by a hydraulic conveying system (slurry system) outside the tunnel and to the separation system at ground level. All these activities can be done while the operator is inside the control cabin monitoring and controlling the parameters [1] (Fig.1).

MTBMs are suitable for the construction of tunnels with an inner diameter ranging from 500mm up to 2,800mm. Fig.2 shows two different microtunneling machine head configurations. For projects under water condition, Microtunnelling TBM can be Earth Pressure Balance (EPB) or Slurry Type. The first one removes the spoil from the face through a Screw Conveyor, whereas the second one by pumping it. For projects to excavate in rock without water pressure, Open Mode excavation is adopted for the MTBM, making the evacuation of the spoil trough a hopper that feeds a belt conveyor. For tunnels with an inner diameter less than 1,500mm, the microtunneling works are performed only with slurry shield, due to space restrictions.

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. Therefore, it is important to calculate the force as accurately as possible. In pipe jacking and micro-tunneling, the jacking pipe carries axial (horizontal) loads during the construction phase and vertical loads from soil, surcharge and live loads both during and after jacking. The exact calculation of these loads will help: design

[1] Dr, Faculty of Construction Mechanical Engineering. National University of Civil Engineering (NUCE).
** Corresponding author. E-mail: chuong40m@gmail.com.*

the jacking pipe safely and economically; select the jacking system capacity; determine the jacking distance and spacing between intermediate jacking station; design the jacking method and equipment; stabilize the face of the excavation to prevent soil failure.

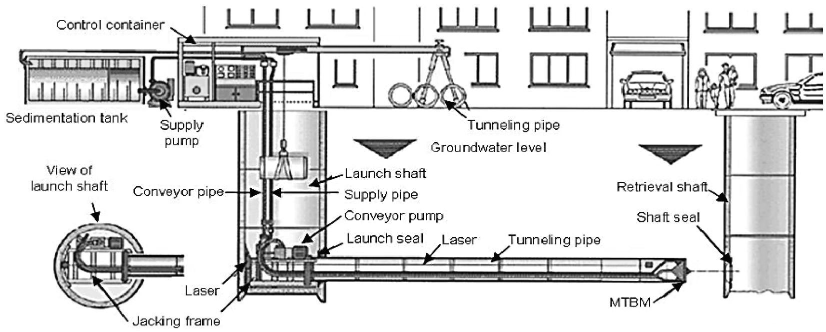
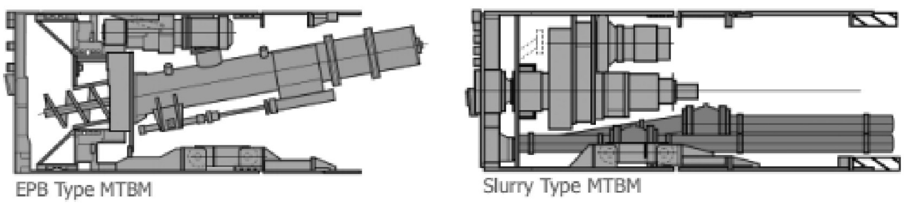


Figure 1. *Schematic of Microtunneling Operation [1]*



a) Earth pressure balance type *b) Slurry pressure balance type*

Figure 2. *Microtunneling boring machines (MTBMs)*

From the late 1970's and early 1980's until now, a lot of practitioners and researchers have developed calculation models for the jacking forces. A number of researchers have conducted both laboratory and field studies to further the understanding of the development of jacking forces during microtunneling and pipe jacking. Many of these studies have included in-depth evaluations of jacking forces in conjunction with a variety of other parameters including face pressure forces or cutting forces, steering corrections, pipe joint deflection, and the effects of lubrication. Other studies have involved statistical analyses of a large number of case histories where basic predictive models were used and empirical data were analyzed to propose factors for both the friction and normal load components of the jacking force. These empirically-based factors were then multiplied by the friction and normal load components of the basic models to predict field behavior on microtunneling projects. Some researchers have investigated to a limited extent the mechanism of shearing at the interface between the soil and the pipes to further isolate the friction that is developed during jacking. In summary, the methods of calculating jacking force can be divided into three main groups: Theoretical methods; Experimental methods and Numerical simulation methods.

There are various studies investigating the jacking force by theoretical derivations [3-5]; by examining the mechanical behavior of soil, jacking force can be calculated while accounting for the overburden pressure on the pipes. Marshall [6] proposed the stress measurements at the pipe–soil interface show that the relations between jacking loads, pipeline misalignment, stoppages, lubrication, and excavation method are highly complex. In [4], Pellet-Beaucour and Kastner pointed out that the frictional force is the main component of the resistance to pipe jacking, and the major controlling factors on friction are lubricated, stoppage, deviation and over cutting… Experimental methods are constructed based on the evaluation of data collected on many rigid jobs. Stein [8] studied the identification of the mechanisms that control interface shearing between pipes and granular materials and the development of a model to predict jacking forces. In engineering design, numerical analysis is commonly applied to the simulation of engineering behavior. 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. 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 of 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 [11-13]. There have been numerous studies exploring and discussing the estimation of jacking force [14,15].

The aim of this paper is to introduce some methods for calculating the jacking force of microtunneling and usual problems will encounter when applied them in Vietnam conditions.

2. Jacking force models

The total jacking force required to propel the tunneling machine and pipe sections forward must overcome the forces associated with face pressure on the machine and friction of the machine and pipeline. The face pressure force acts on the front of the machine and originates from groundwater and earth pressures. The frictional force develops between the surrounding soil and the exposed outer surface area of the tunneling machine and installed pipe sections. The face pressure component relates to the depth of burial and is estimated based on the soil and groundwater conditions at the site. The face pressure component of the jacking force remains theoretically constant if the depth of soil over the pipeline is constant. However, the frictional force increases as the drive length increases. As a result, longer drives require greater jacking forces.

2.1 Theoretical methods of total jacking force

In general (Fig.3), the theoretical formula of total jacking force is:

$$P = P_p + P_f + P_w \qquad (1)$$

where P is total jacking force (kN); P_p is Penetration resistance (kN); P_f is friction between soil and pipe due to soil pressure (kN), P_w is friction between soil and pipe due to pipe weight (kN).

The friction between soil and pipe due to pipe weight (Pw) is calculated: $P_w = \mu.G.L$ (2)

with μ is coefficient of friction between soil and pipe; G is weight per unit length of the pipe (kN/m), L is jacking length (m).

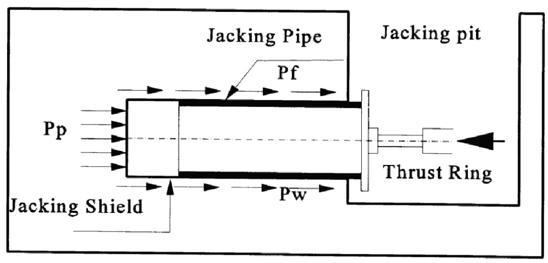


***Figure 3.** Components of the Jacking Force during the construction phase [7]*

The penetration resistance (P_p) is identified depending on the types of excavation. It is called cutting edge resistance when an open jacking shield or an auger microtunneling machine is used and face resistance when a closed boring machine such as a slurry microtunneling machine is used [8].

- The cutting edge resistance (P_p): can be calculated according to the following two methods:

+ Shear strength resistance method:

$$P_p = (\gamma.H.tan\phi + c)\lambda.\pi.D_0.t \qquad (3)$$

where γ is soil density (kN/m^3); H is the depth of soil cover (m); ϕ is angle of internal friction (0); c is soil cohesion (kN/m^2); λ is the coefficient of load bearing capacity (see Fig.4); D_0 as cutting edge diameter (m); t as cutting edge thickness (m).

***Table 1.** Statistically determined cutting edge force based on site records [8]*

Soil type	Cutting Edge Force, kN/m
Gravel, sand	5.29 ± 1.85
Loamy sand	6.21 ± 1.85
Loam	9.08 ± 1.85
Loam stones	9.27 ± 1.85

The value of P_p in equation (3) can be also chosen in (Table 1) [8].

+ Passive earth pressure method: $P_p = \pi.D_o.t.\gamma.(H + D_o/2).\tan^2(45 + \phi/2)$ (4)

- The face resistance (P_p) is composed of the following two components [8, 9]: Boring head contact force on the face (P_1) and Hydraulic force in the suspension chamber to support the face and remove the soil (P_2).

$$P_p = P_1 + P_2 \qquad (5)$$

+ The boring head contact force on the face (P_1) is calculated as follows:

$$P_1 = \frac{\pi}{4} d_1^2.p_b,\ (kN) \qquad (6)$$

where d_1 as the boring head diameter (m) and p_b is the boring head contact pressure (kN/m^2).

To satisfy: $\gamma(H + d_1/2)k_A > P_1 > \gamma(H + d_1/2)k_p$

with k_A is the coefficient of active earth pressure, $k_A = tan^2(45 - \phi/2)$; k_p is the coefficient of passive earth pressure $k_p = tan^2(45 + \phi/2)$.

+ The hydraulic supporting force in the suspension chamber (P_2):

$$P_2 = (1.1 \div 1.2)\frac{\pi}{4} d_{sh}^2 . p_w, \ (kN) \tag{7}$$

where d_{sh} is inside diameter of the shield tunneling machine (m); p_w is water pressure (kN/m^2), $p_w = \gamma_w . h$ with γ_w as the density of water (kN/m^3), h as the depth of water column at the bottom of the pipe (m).

There are many methods to calculate the frictional resistance (P_f), but there is a great variance between the results of these methods. The varying results from the different assumptions and concepts that each method is based on. [7] compared Marston's formula, Terzaghi's silo theory, the Kubota method and Japan Sewerage Association's modified formula to the actual job. They indicated that the results from the Marston's formula are more accurate than the other methods.

Figure 4. *Coefficient of load bearing capacity (λ) vs Angle of frection (ϕ)*

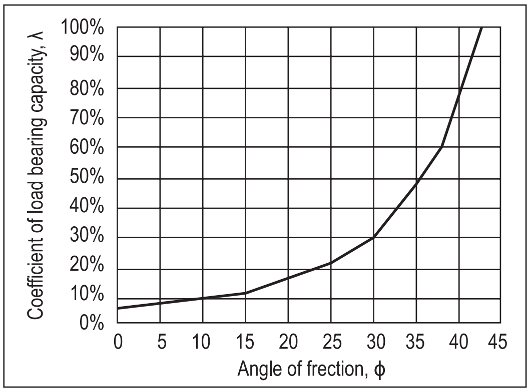


Table 2. *Standard values for coefficient of friction (μ) [8]*

For static friction	
Concrete on gravel of sand	μ = 0.5 to 0.6
Concrete on clay	μ = 0.3 to 0.4
Asbestos cement on gravel or sand	μ = 0.3 to 0.4
Asbestos cement on clay	μ = 0.2 to 0.3
For sliding friction	μ = 0.5 to 0.6
Concrete on gravel of sand	μ = 0.3 to 0.4
Concrete on clay	μ = 0.3 to 0.4
Asbestos cement on gravel or sand	μ = 0.2 to 0.3
Asbestos cement on clay	
For fluid friction	
When using betonite suspension as supporting and lubricating fluid	0.1< μ <0.3

The frictional resistance (P_f) is calculated following the Marston's formula as:

$$P_f = \mu . V . \pi . D . L \tag{8}$$

where is the average coefficient of friction (see Table 2, 3); ϕ is angle of internal friction; D is the outside diameter of the pipe (m); L is the jacking length (m); V is the average normal force along the outside surface of the pipe (kN/m):

$$V = C_t . B(\gamma . B - 2c) \tag{9}$$

with γ as the unit weight of soil above the pipe (kN/m^3); B as the maximum width of trenchless excavation (m); c as cohesion coefficient (kN/m^2) (see Table 4); C_t is load coefficient:

$$C_t = \frac{1 - e^{-2k.\mu.H/B}}{2k.\mu} \tag{10}$$

where e as base of natural logarithms; k as Renkine's ration of lateral to vertical pressure, $k = (1 - \sin\phi)/(1 + \sin\phi)$.

2.2 Empirical methods

The empirical equation to calculate the jacking force [8] is: $P = P_p + JF_{frict}$ (11)

Table 3. *Surface friction angles and coefficients [10]*

Soil type	RCP		Steel/FRP	
	ϕ	μ	ϕ	μ
Sandy gravel, clean	30	0.58	28	0.55
Sandy gravel, silty	22	0.40	23	0.42
Dry medium sand	30	0.58	28	0.55
Dam sand	31	0.60	28	0.55
Saturated sand	30	0.58	26	0.49
Dry silt	30	0.58	28	0.53
Wet silt	22	0.40	20	0.36

Table 4. *Typical values for soil pipe Adhesion and Cohesion [10]*

Pipe Material	Soil	Cohesion (kN/m^2)	Adhension (kN/m^2)
Concrete	Soft	0-36	0-33.5
	Firm	36-71.8	4.8-43.1
	Stiff	71.8-143.6	43.1-62.2
Steel/FRP	Soft	0-36	0-28.7
	Firm	36-71.8	28.7-71.8
	Stiff	71.8-143.6	-

where JF_{frict} is the friction component of the jacking force (kN):

$$JF_{frict} = \mu \frac{\gamma . r. \cos(45 + \phi / 2)}{\tan\phi} . \pi . D . L \tag{12}$$

with *r* is the pipe radius (m), *D* is the outer diameter of pipe (m). The values of interface friction coefficient between soil and pipe *μ* are taken from the table 5.2 in [8] for all pipe materials.

P_p is penetration resistance (kN) can be calculate follow empirical equation in [7] when a slurry micro-tunneling machine is used: $P_p = 13.2\pi DN$ (13)

where *N* as the number of impacts/standard penetration test (number of impacts/30cm) (Fig.5).

Another method proposed by the Japan Micro-Tunneling Associate - JMTA (2000) [3] which commonly used in the world. The jacking force can be expressed as:

$$P = F_0 + \pi . B_c \, \tau_0 . L \tag{14}$$

F_0 is the internal resistance force:

$$F_0 = (P_e + P_w).(D/2)^2 . \pi \tag{15}$$

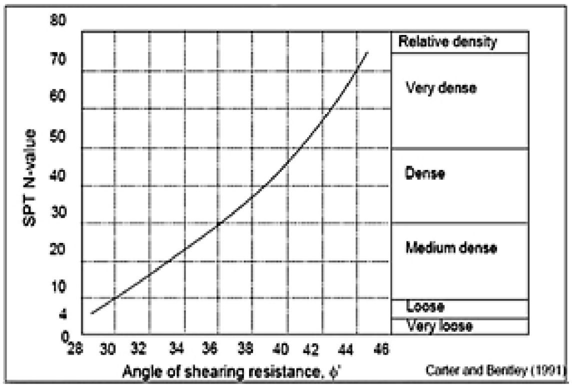
where P_e is the jacking force per unit area of excavation face (kN/m²), P_w is the slurry pressure (kN/m³).

τ_0 is the shear stress between the pipe and the soil:

$$\tau_0 = c + \sigma . \mu \tag{16}$$

with *σ* is the earth pressure; *c* and *μ* are chosen following table 3 and table 4.

Figure 5. *Standard penetration test N - value vesus Angle of shearing resistance*



2.3. Numerical simulation methods

The jacking force formulas under the condition of mudstone formation applying slurry balance jacking for reinforced concrete pipe [16]:

$$P = \begin{cases} when\, L < 100m : K(86\pi . D . L^{-0.57} + P_1),\ kN \\ when\, L \geq 100m : (4 \div 5)K.\pi . D . L + K . P_1,\ kN \end{cases} \tag{17}$$

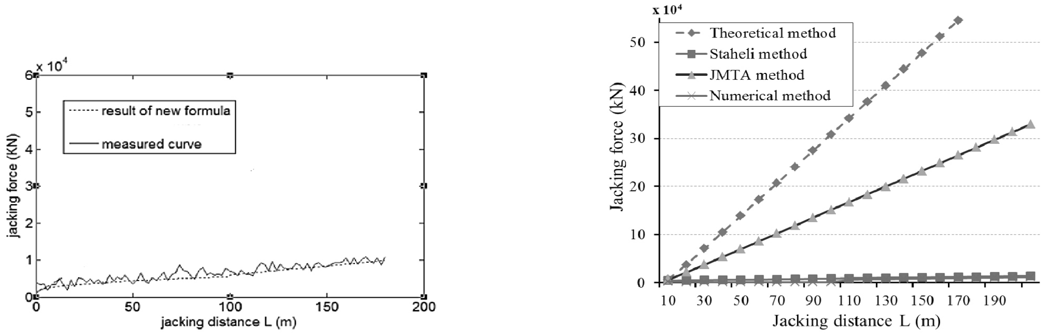
where *K* is the safety factor, P_1 is the penetration resistance: $P_1 = \frac{\pi}{4} D^2 . H . \gamma$, (KN). *H* is the soil thickness above the pipeline (m).

3. The comparison between real project and three different calculation methods

In Vietnam, there were no underground works to be constructed by jacking so there is no real data about the jacking forces. Therefore, in this article use the jacking force data in the paper [16] to make comparisons. The crossing formation is mudstone and using the concrete pipes with the thickness of soil layer below underground water level h_1 = 4m, the soil thickness above the pipe *H* = 7m, the external diameter of pipe *D* = 2.86m, the inner diameter of pipe D_1 = 2.4m, the internal friction angle ϕ = 42.5°, the cohesion coefficient *c* = 112 kN/m², the unit weight of soil γ = 21.5 kN/m³, the weight per unit length of pipe *G* = 44.7 kN/m. This project used a balance slurry closed shield machine has the boring head contact pressure p_b = 300 kN/m², the jacking force per unit area of the excavation face P_e = 500 kN/m².

Fig.6 shows the comparison diagram in the case no lubricate was used (*μ* = 0.4) and the actual jacking force versus numerical method. It reveals that all formulas have a linear relationship of friction with the outside surface area of the pipe. The results from Staheli and Numerical formulas are more accurate than those from theoretical and JMTA methods. Moreover, the results of theoretical and JMTA calculation are much larger than observed jacking force, especially since as the jacking distance increases, the theoretical value increases linearly, even though observed data displays an increase of functional power sometimes big and sometimes small. Power amount is determined by the momentary effect of grouting, which also indicates that the observed data is the real embodiment of grouting effect. So, the results tend to be larger than the true value when calculating the jacking force. In addition, the difference in value between the methods is due to the way calculates of the friction force components in each method.

Fig.7 presents a case using lubricant (μ = 0.1), in which the calculation values follow the theoretical method and Staheli method was reduced as high as 50%, and 25% for JMTA method compare to the unlubricated case. But the numerical formula has a value nearly no change (see Fig.8).



a) Numerical method vs. Measured data [16]   b) Comparison diagram of different methods

Figure 6. *Comparison diagram in the unlubricated case*

Applying to calculate for a project in Vietnam that is "The water system supplies for the chain of towns: Son Tay - Hoa Lac - Xuan Mai - Mieu Mon - Hanoi - Ha Dong". The project uses steel pipe with the external diameter of pipe D = 1.89m, the inner diameter of pipe D_1 = 1.8m, the weight per unit length of pipe G = 64.46 kN/m, the long distance of the pipeline is 204m, the soil thickness above the pipe H = 3m, the crossing formation is clay gravel, the internal friction angle ϕ = 14°, the cohesion coefficient c = 10 kN/m^2, the unit weight of soil γ = 26.754 kN/m^3, N = 4 ÷ 9. This project used a balanced earth closed shield machine has the jacking force per unit area of the excavation face P_e = 328 kN/m^2. This project could not use the equation (17) because do not ground water upper the pipeline. So the jacking force could be calculated follow theoretical and empirical methods for the case has not ground water above pipeline.

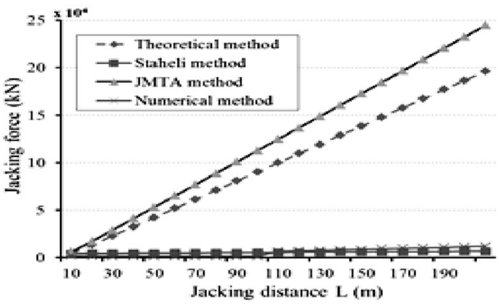
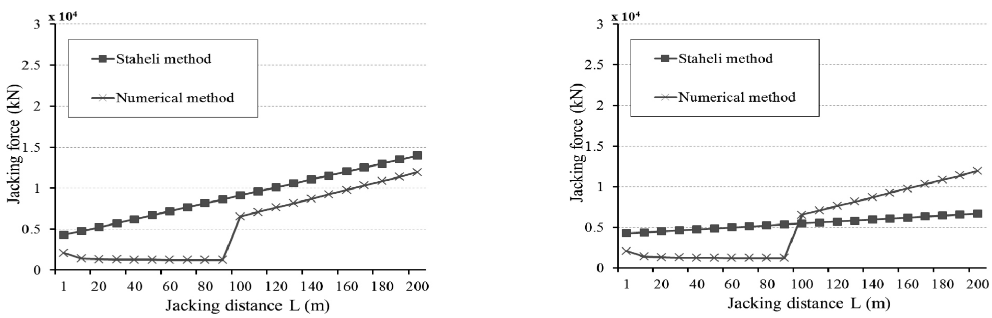
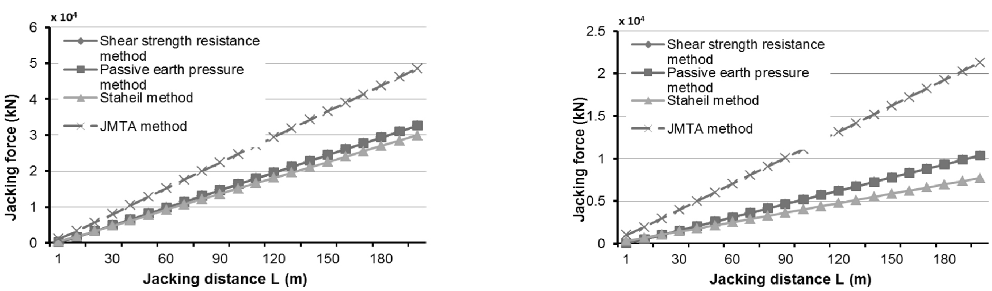


Figure 7. *Comparison diagram when using lubricate (μ = 0.1)*



a) Unlubricated   b) Using lubricate (μ = 0.1)

Figure 8. *Staheli's method versus Numerical method*



a) Comparison diagram in the unlubricated case   b) Comparison diagram in the lubricated case

Figure 9. *Comparison diagrams*

Fig.9 shows the comparison diagrams in the case no lubricate was used (μ = 0.4) and the case use lubricates (μ = 0.1). It reveals that the JMTA method is more conservative than the other methods, as expected. The results from shear strength resistance and passive earth pressure formulas are nearly same values. This figure also indicates that the longer distance of pipeline, the higher difference values between methods. Therefore the engineers need to careful when choosing the mẹthod to calculate the require jacking force.

4. Conclusions

There are many techniques to calculate the jacking force, all of them assumed that the jacking force is the sum of the penetration resistance and the frictional resistance due to soil and pipe's weights. The paper presents three basic methods to calculate the jacking force: theoretical method, empirical method and numerical method using historical data.

The variation between these methods is significant. More study supported by field measurements is required. The required studies should include studying the records of previous jacking jobs in various soil conditions and the soil behavior around the pipe. For calculation, the jacking force should have adequate factors such as soil conditions, the degree of reliability of the approximation of the soil parameters, etc. Each method requires different numbers of parameters, so be careful when choosing the calculation method.

For reducing the friction resistance, can be used lubrication of the outside surface of the pipe. Lubrication is generally recommended around the whole perimeter of the pipe and along the whole length of the drive.

References

1. Martin E.H. (2006), *Microtunneling with Herrenknecht MicroMachines*, Colorado School of Mines.

2. Staheli K. (2006), *Jacking Force Prediction: An Interface Friction Approach Based On Pipe Surface Roughness*, Ph.D dessertation at Georgia Institute of Technology.

3. Japan Micro Tunnelling Association (2000), *Pipe Jacking Application*, JMTA, Tokyo.

4. Pellet-Beaucour A.L., Kastner R. (2002), “Experimental and analytical study of friction forces during microtunneling operations”, *Tunneling Underground Space Technologies*, 17(1):83-97.

5. Chiang W.M. (2006), *Analysis of Jacking Force in Short Sewer Pipe*, Master’s Thesis, Department of Civil Engineering, National Central University, Taiwan.

6. Marshall M. (1998), *Pipe-Jacked Tunnelling: Jacking Loads and Ground Movements*, Ph.D. dissertation at University of Oxford.

7. Atalah A. L., et al. (1994), *Estimating the Required Jacking Force*, Construction Management Faculty publications.

8. Stein D., Möllers K., Bielecki R. (1989), *Microtunneling Installation and Renewal of Nonman - Size Supply and Sewage Lines by Trenchless Construction Method*, Berlin: Ernst & Sohn, Verlag fur Architektur and Wissenschaften, 1st editor.

9. Hancher D.E., White T. D., Iseley D.T. (1988), *Construction Specifications for Highway Projects Requiring Horizontal Earth Boring and/or Pipe Jacking Techniques*, Purdue University.

10. Winterkorn H., et al. (1975), *Foundation Engineering Handbook*, New York: Van Nostrand Reinhold Company.

11. Barla M. (2006), “Analysis of jacking forces during microtunnelling in limestone”, *Tunn. Undergr. Space Technol.*, 21 (6):668-683.

12. Barla M. (2013), “A method to design microtunnelling installations in randomly cemented Torino alluvial soil”, *Tunn. Undergr. Space Technol.*, 33 (1):73–81.

13. Li H. (2012), “Analysis of Jacking Force for Rectangular Pipe Jacking Machine”, *Przeglad Elektrotechniczny*, 88.

14. Chapman D.N., Ichioka Y. (1999), “Prediction of jacking forces for microtunnelling operations”, *Trench. Technol. Res.*, 14 (1):31-41.

15. Röhner R. (2010), “Calculation of jacking force by new ATV A-161”, *Tunn. Undergr. Space Technol.*, 25 (6):731-735.

16. JianshiBai, et al. (2013), *Analysis and Calculation of Jacking Force in the Mudstone Formation*, Pipeline ASCE.