**Stratum properties.** Geological investigation reports show the site geological conditions by drilling hole among the construction fields. The strata are approximately horizontally distributed but there are great differences between each other. It was well proved during the difficult dewatering construction in 74# shaft. The basic strata attributes are shown in Table 1.

**Table 1. Illumination of the construction site strata hydraulic permeability**

| Strata number | Soil Types | Permeability coefficient $k$ (m/d) | Hydraulic permeability |
|---|---|---|---|
| ② | Silt | 0.5 | Weak |
| ②1 | Silt | 0.005 | Micro |
| ②2 | Silt | 5.0 | Normal |
| ③ | Clay soil | 0.005 | Micro |
| ④ | Fine sand | 3.0 | Normal |
| ④1 | Silt | 0.3 | Weak |
| ④2 | Silty clay | 0.001 | Micro |

## AFFECTING FACTORS AND CALCULATION OF JACKING FORCE

Pipe jacking force is directly related to the success or failure. Accurate estimating of the jacking force has important significance to pipe jacking project. It is necessary to take the jacking force into account when designing the driving/reception shaft, selecting the jacking equipment and the pipe to be jacked (Tang, 2004). The factors influencing the jacking force during pipe-jacking construction are as follows: strata properties, dimension and burial depth of the pipe, driving length, pipe material, overcut, annulus lubrication, pipe outer surface roughness, and construction technology (Ma, 2008).

### Jacking force influencing factors

***Strata property and groundwater***

Strata property mainly includes soil density, cohesive strength, internal friction angle, sand-carrying capacity, groundwater level.etc, specially the circumferential soil property around the pipes. The value of sand-capacity would affect the friction factors between the sewer and circumferential soil. Also the alteration of groundwater level influences the effective density. Consequently, the frictional resistance will be changed together with the Strata property modify and influence the value of jacking force.

When the project was constructed below groundwater table, the alternation of the groundwater will lead to the change of the normal pressure applied to the pipe exterior surface and then change the skin friction. As well, groundwater acts against water pressure on the driving face and influences the jacking resistance force.

***Pipe dimension, pipe burial depth and material***

Direct proportion caliber, pipe range, burial depth, synchronously friction coefficient would vary along with the degree of roughness changing between the pipe and circumferential soil. Smooth joint and exterior lubricant coating can reduce the jacking friction effectively.

***Grouting results***
Lubricating slurry was injected into the annular between the soil and the pipelines to reduce the friction between the pipeline and soil. According to the site measurements, effective lubrication can reduce the initial pipe jacking force to 25%~30%.
Overcut ratio
It is the ratio between the external diameter of the cutter head and the external diameter of the product pipe. America Southborough Industry College had done some study of overcut ratio influence on the pipe jacking force and found that the jacking force was in a certain lower condition if the overcut ratio is larger than the optimal overcut ratio. But the jacking force was increasing quickly along with the increasing overcut ratio.
***Construction factors***
The interruption of jacking process can also cause the significant increase of jacking force. The surrounding soil can embrace the jacking pipelines and enlarge the friction force between the pipe and soil. It is ineluctable to face the inaccuracy away from designed jacking path. So the direction rectification during the pipe installation may result in jacking force increase.

**Calculation of pipe jacking force.** Pipe-jacking force can be predicted using the following formula （Zhao, 2004; Ma, 2008):

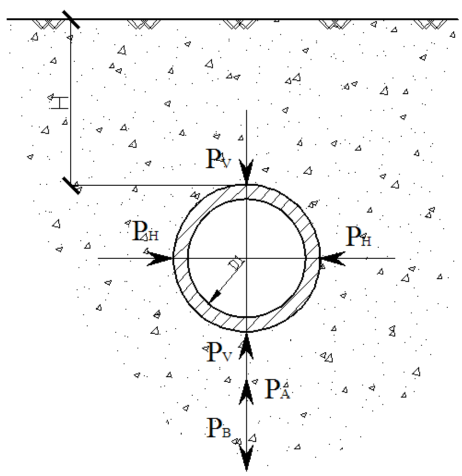


**Figure 3. Analyses of total external pressure on pipe**

$$R_f = K\left[f\cdot\left(2P_v + 2P_H + P_B\right) + P_A\right] \qquad (1)$$

where：

$R_f$ =calculated pipe jacking force, KN；

$P_v$ = vertical pressure of soil above the top of pipe, KN;

$P_H$ = lateral soil pressure, KN;

$P_B$ =Total weight of planned jacking pipeline, KN;

$f$ =Friction coefficient between pipe and soil; see Table 2 (Gao, 1984);

$P_A$ =Penetration resistance, KN;

$K$=factor of safety, generally given 1.2.

**Table 2. Values of friction coefficient ($f$)**

| Type of soil-layer | concrete reinforced pipe | | | Steel pipe | | |
|---|---|---|---|---|---|---|
| | desiccation | moist | General value | desiccation | moist | General value |
| Soft soil | -- | 0.20 | 0.20 | -- | 0.20 | 0.20 |
| clay | 0.40 | 0.20. | 0.30 | 0.40 | 0.20 | 0.30 |
| Sandy clay | 0.45 | 0.25 | 0.35 | 0.38 | 0.32 | 0.34 |
| silt | 0.45 | 0.25 | 0.35 | 0.38 | 0.32 | 0.34 |
| Sandy clay | 0.47 | 0.35 | 0.40 | 0.48 | 0.32 | 0.39 |
| Gravel clay | 0.50 | 0.40 | 0.45 | 0.50 | 0.50 | 0.50 |

Vertical soil pressure can be estimated by Eq (2):

$$P_V = K_p \cdot \gamma \cdot H \cdot D_1 \cdot L \qquad (2)$$

where：

$K_p$ =factor of vertical soil pressure, see Figure 4;

$\gamma$ soil density, KN/m$^3$;

$H$ =soil height above the top of pipe, m;

$D_1$ =pipe outside diameter, m;

$L$ =Length of jacked pipe, m.

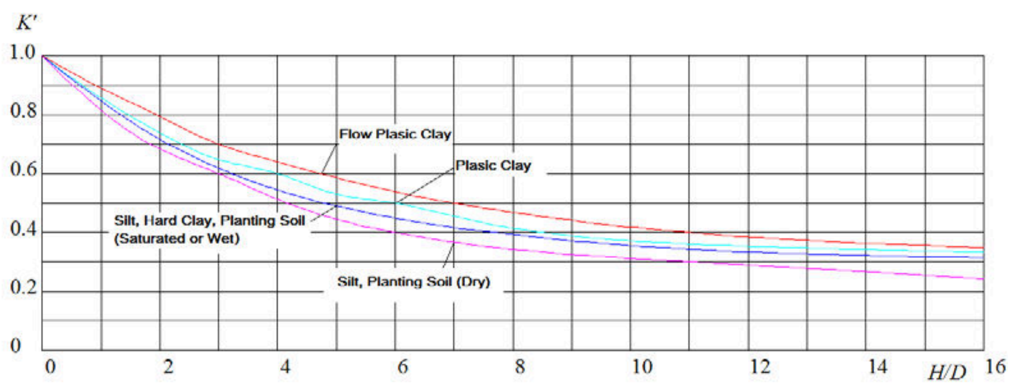


**Figure 4. h/d-k' curves**

The equation 3 can be used to determine the lateral soil pressure $P_H$:

$$P_H = \gamma \cdot \left( H + \frac{D_1}{2} \right) \cdot D_1 \cdot L \cdot \tan^2 \left( 45^\circ - \frac{\varphi}{2} \right) \quad (3)$$

where :

$\varphi$=internal friction angle of soil, °;

The weight of the planned jacked pipe $P_B$ can be calculated using equation 4:

$$P_B = G \cdot L \quad (4)$$

where :

$G$=weight of pipe per meter, KN/m;

$L$=total length of the jacking pipes.

The penetration resistance acting on the cutter head is depending on the soil pressure ahead the cutter head (Yu, 1998). . The total load applied to cutter head is show in Figure 5.

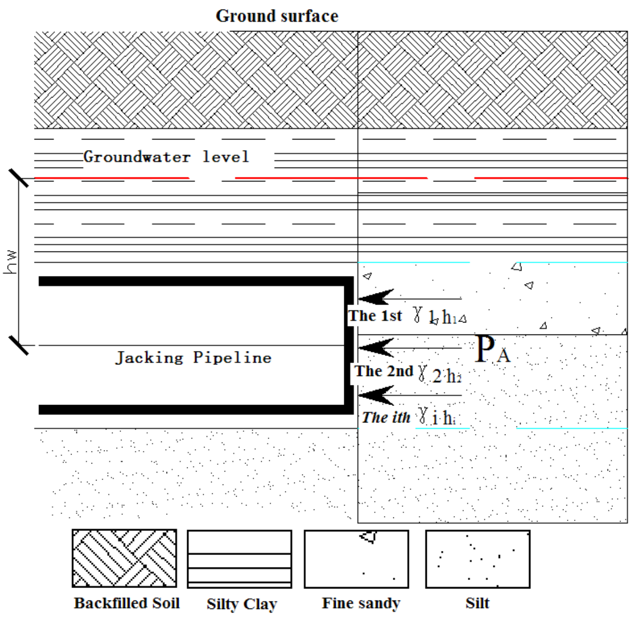


**Figure 5. Penetration resistance calculation schematioc diagram**

$$P_A = \frac{1}{4}\pi D^2 \left[ K_0 \sum (\gamma_i h_i) + \gamma_w h_w \right] (\text{Static}) \quad (5)$$

where :

$\gamma_i$=density of the soil in layer $i_{\text{th}}$, or buoyant density for silt clay, saturated density for clay soil, KN/m$^3$ (when the soil is below the groundwater table);

$h_w$=height of ground surface to pipe axis, m;

$\gamma_w$=density of water, KN/m$^3$;

$D$=pipe outside diameter, m;

$K_0$ =coefficient of static soil pressure;

According to the field investigation report of test section and strata parameters, we can get the equation (6) of jacking force $R_f$ and jacking length $L$ after combined Eq (2)、(3)、(4)、(5) with (1):

$$R_f = 107.112L + 595.23 \qquad (6)$$

The relationship between $R_f$ and $L$ is linear (see **Figure 6**):

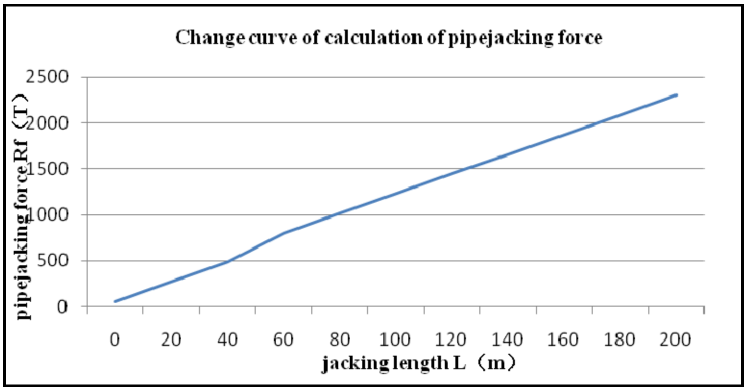


**Figure 6. Calculated jacking force curves without grouting drag reduction**

From the Figure 6 It can be easily found that $R_f$ and $L$ has linear relationship.
For long distance pipe jacking projects, the grouting effect is depending on the performance of thixotropic slurry. The jacking force can be calculated by Eq (7) when considering the influence of grouting (Yu, 1998).

$$R_f = K(F + P_A) \qquad (7)$$

$$F = \pi DLf' \qquad (8)$$

where :
$f'$ = average friction between pipe and soil unit area, KN/m$^2$, generally given 4~12 KN/m$^2$， according to the construction experience in soft strata.
It was found that the relationship between $f'$ and L isn't linear any more but power exponent based on the field actual measurement and analysis. In the initial stage of driving, the friction force per unit area is quite large, but it presents a stable value with increasing distance of the jacking length. To summarize, the paper gives the definition for $f'$: for soft strata, when $L \le 100$ m, $f'=(20\sim50)\,L^{-0.5}$ KN/m$^2$; and $L>100$m, $f'=2\sim8$KN/m$^2$, multiplication by corresponding coefficient for other strata $f'$ value (Xiang et al., 2006). The penetration resistance acting on the cutter head is determined by Eq (5) again.
There are different calculation equations for different value $L$ as follows:

$$R_f=\begin{cases} L\leqslant 100 & \begin{cases} 135.648\sqrt{L}+595.2 \\ 339.12\sqrt{L}+595.2 \end{cases} \\ L>100\text{m} & \begin{cases} 13.5648L+595.2 \\ 54.2592L+595.2 \end{cases} \end{cases}$$

The curves between $R_f$ and $L$ is shown in Figure 5.

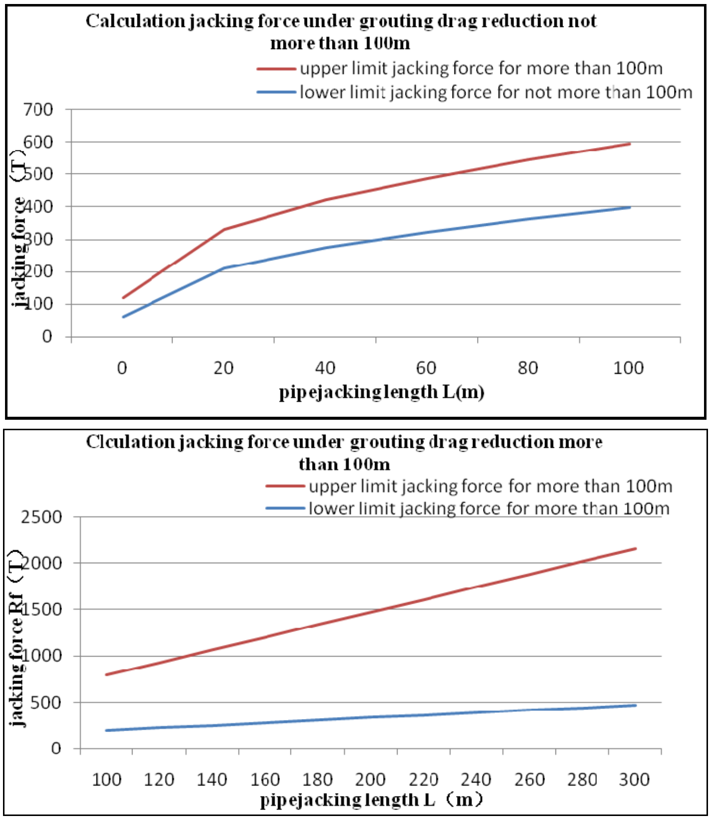


**Figure 5. Theoretical calculation jacking force under grouting drag reduction more than 100m**

By comparing Eq (6) and (7), there are great differences in the pipe jacking force. It is necessary to predict the reasonable jacking force according to the empirical formula and technical formula, which will determine the project design, equipment selection and maximum jacking force. Then it is effective to control the grouting result from thixotropic slurry and grouting pressure and play a role in reducing the pipe jacking force.

**Field data analysis and comparison with predicted values**

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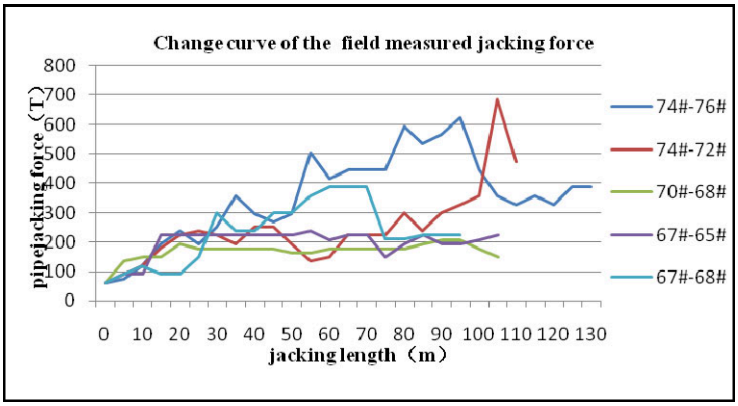


**Figure 6. Relationships between the jacking force and jacking length**

The jacking loads of all the five test sections have been recorded. The relationships between pipe jacking force $R_f$ and jacking length $L$ are shown in Figure 6. The jacking force from the 74# to 76# fluctuates intensely, and in the section from 74# to 72#, there appeared unusual fluctuation and the reacting wall was destroyed due to the overloading on it; from 67# to 68#, the jacking force increased naturally with partially rapid jacking force increasing. There give the detailed reasons for these unusual fluctuations as follows:

- Property change of the jacking strata. Taking the 74#-76# section for example, there have been appeared several times during the construction, approximately 25% of 5~20 mm diameter hard gravel were encountered and the torque appeared visible fluctuation, this phenomenon was also appeared in the other test section, which can be seen from the mud circulating system.
- Construction interruption influences the pipe jacking force. Because of the appurtenance breakage the construction had to be halted nearly 4 hours to repair or the replace the appurtenance. The pipe jacking force became much larger than the normal jacking when the construction started again. The reason is the soil around the jacking pipeline clasp the pipes firmly and lead to the increase of the friction between the soil and the pipelines.
- The influence of groundwater on pipe jacking force. Abundant groundwater and the ancient marshland result in the complex geological condition in the 74# shaft, and it is necessary to dewater effectively during the pipe jacking construction.
- Overcut ratio set. The overcut ratio of section 74#-76# was 10 mm, but 15mm in the following test section project. Pipe jacking forces in the following sections were generally reduced by the new set of overcut ratio.
- The influence of the thixotropic slurry property. Grouting in long distance pipe jacking is critical to reduce the pipe jacking force. Making good use of the grouting results can guarantee the project completed smoothly and on time. The initial property of the thixotropic slurry was composed by general bentonite without high

polymer Na-CMC. The reduction of the grouting was limited in short jacking length; with the increasing jacking length the lubrication became limited and non-linear increasing. The site engineer adjusted the property of the thixotropic slurry by adding high polymer and other reduction materials. The drag reduction of grouting became regular in the following test section.

## JACKING FORCE CALCULATION FORMULA CORRECTION FOR COMMON STRATA

By the comparison between the actual and predicted jacking forces, the actual jacking force was in the range calculated by Eq (7). The strata are mainly silt and clay in most of reconstruction of rain and sewage water of urban drainage system. Additionally the groundwater influence on the pipe jacking force would vary in complex rule. The Table 3 shows the calculating equation for different types of strata:

**Table 3. Parameter selections under normal strata conditions**

| Jacking Force Calculation Formula | Strata Property | Parameter Selection |
|---|---|---|
| $R_f = K(P_A + \pi D L f^{'})$ | Silt stratification, soft-hard clay stratification | When $L \le 100$m, $f'=(20\sim30)\ L^{-0.5}$ KN/m$^2$ And $L>100$m, $f'=2\sim3$KN/m$^2$ |
| | hard-rigid clay stratification, medium compact sand seam | When $L \le 100$m, $f'=(30\sim40)\ L^{-0.5}$ KN/m$^2$ And $L>100$m, $f'=3\sim5$KN/m$^2$ |
| | Compacted sand seam, gravel stratum | When $L \le 100$m, $f'=(40\sim50)\ L^{-0.5}$ KN/m$^2$ And $L>100$m, $f'=5\sim6$KN/m$^2$ |

NOTE: the head-on resistance determined by Eq (5).

## CONCLUSION

- It's adequate to adopt slurry balance pipe jacking method to install sewer pipelines whose buried depth greater than or equal to 5 m and lager than 600 mm diameter.
- For difference types of strata in construction site, different methods should be adopted to predict the pipe jacking force. Choosing corresponding coefficient for different types of geological conditions is advisable.
- To guarantee the continuity and high effectiveness construction, it's necessary to adjust the construction technology of pipe jacking to adapt the sewer pipelines installation.
- Lubrication has critical influences on the middle and long distance pipe jacking construction.

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# Construction Control in the Pipe Jacking of a Sewage Interception Project

Yang Zhuanyun[1]

[1]Yang Zhuanyun, Sichuan College of Architectural Technology, Deyang, China, 618000; Phone: +86-138-8108-1454; Fax: +86-838-2651997 ; email: zhuanyun@gmail.com

## ABSTRACT

With the engineering practice of a Sewage Interception Project, the essential technical measures on the construction of pipe jacking during long-distance were discussed, which mainly include the construction of the jacking shaft, the jacking pipes breakthrough technique, correction and guidance in construction, partial air pressure balance method when jacking through drift sands or flow plastic soil, drag-reduction using thixotropic slurry, arrangement of the pipe section with different types of grouting holes, soil reinforcement using cement slurry to replace thixotropic slurry after the completion of the jacking and interjack station techniques in long-distance pipe jacking. After being jacked through deviation of the jacking pipe axis was within 60mm and deviation of the elevation was within 50mm; soil movement had no significant effect on the pipelines nearby; construction proceeded fast as earthwork was effectively reduced; damage to environment was limited to minimum because of low noise in underground construction and the concentrated emission of soil and slurry. The result showed that good economic and social benefit was achievable using the above-mentioned technical measures in long-distance pipe jacking.

## KEYWORDS

Pipe jacking; Essential technical measures; Construction control methods

## INTRODUCTION

With the advancing of urbanization process, the development and utilization of underground space are drawing more and more attention. Pipe jacking, as a tunneling construction technology, is gaining wider and wider application because of its advantage in laying pipes without excavating surface soil. However, pipe jacking will inevitably cause the displacement of both surface and underground soil body and generate an additional stress in the soil, which, if the displacement is too large, will cause damage to the surrounding structures and adjacent underground pipelines.