Jacking Force Estimating and Site Measured Data Analysing of a complex Curved Long Distance and Large Diameter Pipe Jacking

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Abstract. This paper presents the jacking force estimating and the measured data analysing of a 3D curved, 413 meters long distance and 3.8 meters external diameter jacking project. The jacking load consists of the face load and friction resistance, and it is influenced by many factors. The widely used estimated method include Chinese cord method, Japanese method and German method, and they all have application conditions, which make them have limitations for engineering application, especially the friction resistance factors are offered by a wide interval. The jacking loads are calculated by the above estimated methods in a 3D curved, 413 meters long distance and 3.8 meters external diameter jacking project, 3 intermediate jacking stations are set according the calculation result. According by the site measured datum in the construction procedure, the composition of the jacking load and its relationship with the jacking distances and the curve radius are analysed, and the frictional residence factors in clay are provided on the class by straight line and curved lines, which provide a basis for similar engineering.

1. Introduction
The total jacking force is the force required to overcome frictional resistance of the pipe string weight and face resistance at the shield. Accurate prediction is important to the design of the jacking pit and thrust wall; selection of jacking equipment (jacking frame and main rams) and jacking pipe wall thickness; the need for and placement of intermediate jacking stations; and lubrication requirements. In modern jacking technology, resistance reduction technique is widely used in the large diameter and long drive pipeline jacking projects, and then the jacking load is consist of face load and lubrication loads which effect on the soil and pipes.

Accurate prediction is important to the design procedure, but the jacking force is dependent upon a number of interrelated and variable factors: the stability and friction characteristics of the geology to be tunnelled through, the self weight and strength of the pipes, the diameter of pipe, the type of excavation method, and the available jacking reaction. In the other hand, the jacking force calculation methods have their own application scope, the major constraint will be the nature of the ground and the ground water characteristics.

An HV cable tunnel with 3200mm internal diameter and 5.91km length is constructed in Fuzhou, hundreds of 3800mm external diameter and 2500mm length concrete pipes are precast in the factory.
and jacked in the tunnel path to form the tunnel. The tunnel is divided into 19 intervals by 20 jacking pits; one of these intervals is 3D curved and 413 meters driving distance, the profile curvature radii are 600.00m in vertical profile, 506.98m and 313.70m in the horizontal profiles; the minimal radius is 82 times to the pipe’s external diameter. In this jacking interval, the HV cable tunnel has to cross under a sewage pipeline, and it’s only 0.6m between HV cable tunnel and the external sidewall of the sewage pipeline’s working pit. This situation put high request forward to the pipe track control and the ground deformation control, and also request a reliable calculation result of the placement of intermediate jacking station.

This paper estimates the jacking force in that interval with Chinese, Japanese and German cord, and arrange the placements of the intermediate jacking stations. The site measured datum is analysis to ensure the calculation formula and their parameters, especially the frictional factors between the soil and the pipe. The calculation and the analysed figures provide a basis for similar engineering.

2. Present calculation methods
There are numbers of calculation methods for pipe jacking force, and only several of them are widely used in engineering practice in China, which included Chinese cord, Japanese method and German method. We are going to introduce them briefly.

2.1. Chinese cord method
Chinese national regulation GB 50268 and trade norm CECS 268 have the same formula in the lubrication pipe jacking force, the formula as:

\[ F_s = \pi D_1 L f_s + P_f \]  

where \( P_f \) is the face load
\( D_1 \) is the external diameter of the jacking pipes
\( L \) is the driving path length
\( f_s \) is the frictional factors between soil and the pipes.

This formula is base on the pipe jacking projects which taking thixotropic slurry as the frictional reduction measure, if not, it’s better to use another suitable formula to estimate the jacking force.

When the pipe jacking excavation method is chosen between slurry balance machine or earth pressure balance machine, the two norms have a same calculate regulation, which used earth pressure on the face multiply by the face area. The difference is in the earth pressure, GB 50268 chooses upper soil weigh as earth weigh, and CECS 268 chooses actual control face pressure.

The two norms almost have the same suggested values of the frictional loads between soil and the pipes, which can be seen in Table 1. the difference is GB 50268 have another specification “When the thixotropic slurry technology is mature and reliable, and the tolerances can form a remain stable, continuous slurry sleeve, the frictional resistance load could be calculated by 3.0~5.0 kPa”.

| Frictional reduction measure | Pipe material | Soft clay | Silty soil | Fine silt sands | Medium-coarse sand |
|-----------------------------|---------------|-----------|------------|-----------------|--------------------|
| thixotropic slurry concrete | 3.0~5.0       | 5.0~8.0   | 8.0~11.0   | 11.0~16.0       |
| thixotropic slurry steel    | 3.0~4.0       | 4.0~7.0   | 7.0~10.0   | 10.0~13.0       |

2.2. Japanese method
Japanese consider that the jacking force consists of three parts: face load, frictional resistance load between pipes and soil, the cohesive load between soil and pipes, the formula as:

\[ P = P_f + f \pi D_1 (q + w) L + \pi D_1 c L \]  

where \( q \) is the vertical load
\( f \) is frictional resistance factor between soil and pipes
c is the cohesion
w is the ground overloading above pipes.
This formula is base on the pipe jacking projects without thixotropic slurry as the frictional reduction measure.

2.3. German method
As the same to Chinese norms, German consider that the jacking force consists of face load and the frictional resistance load between pipes and soil, the formula as:

\[ P = \frac{\pi D^2}{4} B + \pi D f_s \]

where \( B \) is the face pressure
\( f_s \) is frictional resistance factor between soil and pipes
This formula is base on the pipe jacking projects with thixotropic slurry.

2.4. Additional frictional coefficient of axis curve pipe jacking
As we know, driving jacking pipes in a radius would encounter larger frictional resistance than a straight line, so an additional frictional coefficient must be considered in the jacking force estimation. According to experience in Shanghai and Fuzhou, the additional frictional coefficient can be calculated by different radius, they are shown in Table.2.

| Curve radius(R) | 300D | 250D | 200D | 150D | 100D |
|-----------------|------|------|------|------|------|
| Additional frictional coefficient(K) | 1.10 | 1.15 | 1.20 | 1.25 | 1.30 |

Where D is the external diameter of the jacking pipes.

3. Jacking force estimated
Estimating jacking force is quite important procedure in pipe jacking design, but the jacking force is dependent upon a number of interrelated and variable factors, that make it hard to accurate calculated. This chapter will estimate the jacking force in a 413 meters driving distance white 3D curved by the widely used method, and then arrange the displacement of the intermediate jacking stations.

3.1. Project overview
An HV cable tunnel with 3200mm internal diameter and 5.91km length is constructed in Fuzhou, hundreds of 3800mm external diameter and 2500mm length concrete pipes are precast in the factory and jacked in the tunnel path to form the tunnel. The tunnel is divided into 19 intervals by 20 jacking pits; one of these intervals is 3D curved and 413 meters driving distance, the profile curvature radii are 600.00m in vertical profile, 506.98m and 313.70m in the horizontal profiles; the minimal radius is 82 times to the pipe’s external diameter. In this jacking interval, the HV cable tunnel has to cross under a sewage pipeline, and it’s only 0.6m between HV cable tunnel and the external sidewall of the sewage pipeline’s working pit. The plan graph and drive section are shown in figure 1 and figure 2.

3.2. Total required jacking force estimate
As shown in the section, these jacking pipe have to cross the clay sand layer(③), silty clay layer(④). The lubrication measure has been taken, and the jacking force is calculated in Chinese norms method, and the frictional resistance factor is 4 kPa.

The face load near to No.10 pit can be calculated as:

\[ P_f = (18kN/m^3 \times 2.8m + 16.3kN/m^3 \times 9.64m) \times \pi \times (1.9m)^2 = 2353.7kN \]  

The face load near to No.11 pit can be calculated as:
\[ P_f = (18kN/m^3 \times 2.6m + 16.3kN/m^3 \times 10.7m + 19kN/m^3 \times 2.0m) \times \pi \times (1.9m)^2 \]
\[ = 2939.7kN \]

And the frictional resistance load as:
\[ P_f = \pi \times 3.8m \times 4kN/m^2 \times (1.0 \times 180m + 1.25 \times 116.8m + 1.27 \times 67.6m + 1.35 \times 48.6m) \]
\[ = 22800.0kN \]

The total required jacking force equal to:
\[ P = 22800.0kN + 2939.7kN = 25740kN \]

Figure 1. Plane graph of the 3D curved, long distance and 3800mm diameter pipe jacking

Figure 2. Section graph of the 3D curved, long distance and 3800mm diameter pipe jacking
3.3. Inter-jacking stations arrangement

No.10 working pit can only provide 12000kN reaction force forward, which is less than the total required jacking force, so some inter-jack stations have to be placed between the launch pit jacking rig and the tunnelling machine.

According to Chinese standard CECS 268:2008, the number of the total inter-jacking station can be calculated as:

\[ n = \pi D_1 f_i (L + 50)/(0.7 \times f_0) - 1 = \pi \times 3.8 \times 4(413 + 50)/(0.7 \times 12000) - 1 = 2.6 \]  

Where 0.7 is the permissible load of the intermediate jacking station, 12000kN is the design load in this project. According to the calculation, 3 interjacks stations have to be set in the jacking interval from No.10 working pit to No.11 pit. The 0.7 can be used in theoretical calculation, and the rest 0.3 is reserved for the unpredictable incidents. Considered the curved jacking distance and placement, the intermediate stations are set in 40m, 140m and 240m after the excavation machine. Arrangement is shown in Table 3.

Table 3. Arrangement of the intermediate jacking stations in the interval

| Driving distance (m) | 40  | 140 | 240 | 413 |
|----------------------|-----|-----|-----|-----|
| Number of the intermediate stations | 1st | 2nd | 3rd |

4. Site investigated and analysis

Engineers had record the jacking force and jacking distance in the jacking procedure, these site measure data can be used to back analyse the face load and the frictional resistance load.

Curve in Figure 3 shows the relationship between drive distance and jacking force. The reality face load in site measures is 2032kN, which is nearly to the theoretical value 2353.7kN as calculated in formula [4], it can be considered as a deviation of the theory to the reality, or it may be caused by the disturbance in the No.10 working pit construction. No matter what the reasons is, the deviation is less than 10%, the face load is still estimated by theoretical value in the follow up analysis.

The maximum total site measured jacking force is 14230kN, exceed the allowable load of No.10 working pit, but the construction monitoring of the working pit in the jack procedure shows that the maximum displacement of the working pit is less than 30mm in vertical direction, and the construction group determined not to start the 1st intermediate station until the total jacking force reach to 16000kN. None of the 3 intermediate stations started in the pipe jacking procedure.
The frictional resistance load can be calculated by the following formula:

\[ f_s = \frac{(P - P_r)\pi D_f L_f}{(\pi D_l L_f)} \]  \hspace{1cm} (9)

Parameters in formula [9] are the same to the formula [1]. Average frictional resistance load between soil and the pipes is calculated and its relationship with drive distance is shown in Figure 4. The total average frictional resistance load is 2.2kPa, which is less than the predictive value 4.0kPa, and matches the empirical value in PJA’s publications. And if this project using this value to estimate jacking load, the total needed jacking load should be calculated as:

\[ n = \frac{\pi D_f f_s (L + 50) / (0.7 \times f_o) - 1}{\pi \times 3.8 \times 2.2 \times (413 + 50) / (0.7 \times 12000) - 1} = 1.45 \]  \hspace{1cm} (10)

And then the intermediate jacking stations can reduce to 2.

As mentioned above, in the curved jacking intervals, additional frictional coefficient has to be considered. The straight line and curved radii in this interval can be seen in the Figure 4, and the average frictional resistance loads of these intervals are 1.69kPa, 2.85kPa, 2.36kPa, 1.91kPa. Relationship between additional frictional coefficient and radii is shown in Table 4.

| Curve radius(R) | 0   | 158D | 130D | 80D  |
|-----------------|-----|------|------|------|
| Additional frictional coefficient(K) | 1.00 | 1.68 | 1.40 | 1.13 |

From Table 4, we can know that the additional frictional coefficient is exist, and the values are greater than the Chinese experience, but the absolute values are all less than 4kPa.

5. Conclusions

The formulas to calculate the total jacking force all have clear physic meaning and it is convenient to use, but the jacking force is dependent upon a number of interrelated and variable factors, especially the frictional resistance factor influence by not only the soil conditions, but also jacking operations and other incident factors, theoretical calculation is necessary but not accurate, engineering must remember that.

Lubrication is a useful measure to reduce the jacking load, the frictional resistance load is usually less than 4kPa, and the additional frictional coefficient is truly exit in the plane or profile curvature.
According to the site measured data back analysing, the additional frictional coefficient does not necessarily relate to curvature radius.

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