

Technologies of Micro-Disturbance Construction of Pipe-Jacking

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ABSTRACT: As a mature subsurface excavation method, pipe-jacking has already been widely used in many fields of city construction. The fact that the construction environment becomes more and more complicated requires micro-disturbance pipe-jacking. Combining the successful micro-disturbance construction of the pipe-jacking part of Shanghai Expo Power Cable Tunnel, some methods such as the preparations before construction, disturbance controlling during different construction phases and many specific construction technologies are summarized. During pipe jacking, a lot of measures like keeping the stabilization of the excavation surface, controlling the pipe jacking speed, adopting new sludge lubricating sleeve technologies, achieving precise attitude control and conducting timely slurry replacement. It is hoped that this will be helpful to the later micro-disturbance pipe-jacking.

1. INTRODUCTION

The pipe-jacking method is a method of tunnel construction where hydraulic jacks are used to push specially made pipes through the ground behind a tunnel boring machine or shield. With quick development of national economy and wide spread of the city infrastructure, pipe-jacking as a mature subsurface excavation method, has been adopted in many fields of city construction. Nowadays in crowd city, the construction environment becomes more and more complicated. The tunnels always underpass things such as power lines, water lines, subways, buildings, rivers and so on. And in this situation the construction environment must be strictly protected, which means micro-disturbance objective should be arrived.

The pipe jacking method has advantages such as adaptation to various soil layers, reliability, and economical efficiency, etc.; as a result, it is widely used in tunnelling excavation in complicated environment. The study of micro-disturbance pipe-jacking becomes very important. Combining with the successful micro-disturbance construction of the pipe-jacking part of Shanghai Expo Power Cable Tunnel, this paper summarizes the achieving methods and technical requirements of micro-disturbance pipe-jacking.

Shanghai Beijing West Road – Huaxia West Road Power Cable Tunnel (Figure 1) is invested by Shanghai Municipal Electric Power Company to widen the scale of Shanghai power line nest. The line is totally 15.05 km long, the pipe-jacking part of which is 6.22 km long. The pipe-jacking part is divided into 6 parts (table 1). And the main properties of the soil layer are shown in table 2. In the part 12#~13#, the pipe jacking machine underpasses lots of old houses, most of which are one or two storey masonry buildings(Figure 2). And in the part 6#~7#, the pipe jacking machine underpasses Huangpu River and flood walls. The project adopted many methods to minimize the ground movement, which are worthy studying.

Schmertmann (1953) put up with the expression of degree of tunnel construction disturbance and the concept of disturbance classification according to the e-lgp curve of laboratory small load compression test. This paper defines the micro-disturbance as the horizontal and vertical total displacement less than 10 mm and the maximum displacement rate less than 3mm/day.

Table 1 Six parts of the pipe-jacking tunnel

No.	Part	Distance	Diameter	Material
1	7#→6#	842.55m	φ3500mm	Reinforced concrete
2	7#→8#	830.5m	φ3500mm	Reinforced concrete
3	11#→10#	794.63m	φ3500mm	Reinforced concrete
4	12#→11#	1328.64m	φ3500mm	Reinforced concrete
5	12#→13#	1279.37m	φ3500mm	Reinforced concrete
6	13#→14#	1048.66m	φ3500mm	Reinforced concrete

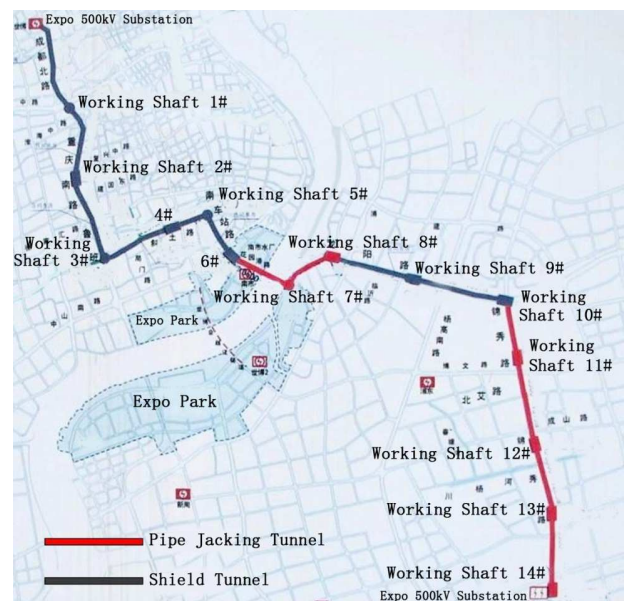


Table 2 Main soil properties of the project

No.	Name	Thick-ness	Water content	Dry unit weight	CU Strength	
		m			c	Φ
			%	kN/m ³	kPa	°
①	Fill	0.50 ~ 7.00	32.4	13.8		
①-A	Creek fill (silt)	0.30 ~ 2.90				
② ₀	Gray sandy power soil	3.80 ~ 16.90	36.7	13.1	2	30.4
② ₁	Yellow silty clay	0.30 ~ 2.60	32.4	13.9	19	18.6
③	Gray silty with power clay inside	0.80 ~ 8.50	39.5	12.5	11	16.9
③-T	Gray clayey silt	0.60 ~ 13.10	32.1	13.9	5	30
④	Gray silty clay	1.00 ~ 12.10	49.3	11.3	11	10.2
⑤ ₁₁	Gray clay	1.10	38.2	12.8	15	13.8
⑤ _{1-T}	Gray sandy power soil	0.60 ~ 6.70	30.2	14.2	5	30.3
⑤ ₁₂	Gray silty clay	2.00 ~ 15.50	33.3	13.6	17	16.8
⑥	Sap green ~grass yellow silty clay	1.60 ~ 7.50	23.2	16.0	47	18.6
⑦ _{1T}	Gray silty clay with power interlayer	2.2~ 7.50	27.7	14.8	6	30.0
⑦ ₁	Grass yellow ~ gray sandy power soil	1.80 ~ 14.7	29.4	14.5	4	32.9
⑦ ₂	Gray power sand	12.0 ~ 33.0	27.6	14.8	2	33.4



Figure 2 Underpassing lots of old houses in Part 12#~13#

2. MICRO-DISTURBANCE CONSIDERATIONS BEFORE CONSTRUCTION

Subject to the surrounding environment, the tunnel circuit sometimes must be curved lines. In this situation, as the radius of curvature gets smaller, the deflection angle of pipe-jacking section gets larger, and the pipe-jacking disturbance increases. To achieve the micro-disturbance construction, the radius of curvature should be set as large as possible in the alignment planning.

Appropriate equipment selecting before construction is also important to control the disturbance during pipe-jacking. Manual of design and construction of underground project gives the instructions of selecting appropriate front device of the boring machine. Combining with the specific geology situation, the selection should be prudent.

3. STAGE DISTURBANCE CONTROL OF EXCAVATION

When the pipe-jacking machine went from the working shaft 7# to the working shaft 6# under Huangpu River, the settlement of flood wall to the east of the river is shown in Figure 3 (measuring points F1~F9 are along flood wall as shown in figure 4). When the pipe went from the working shaft 12 to the working shaft 13 under many houses, a typical curve of the settlements of these houses is shown in Figure 5 (measuring points F179~F184 are shown as figure 6).

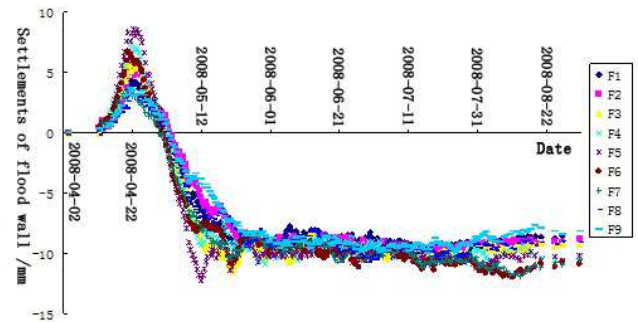


Figure 3 Settlement of flood wall to the east of Huangpu River

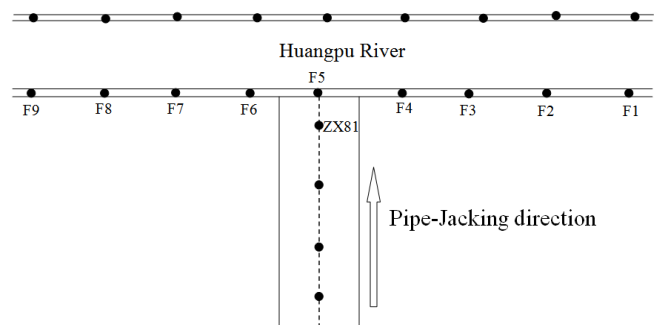


Figure 4 Positions of measuring points F1~F9

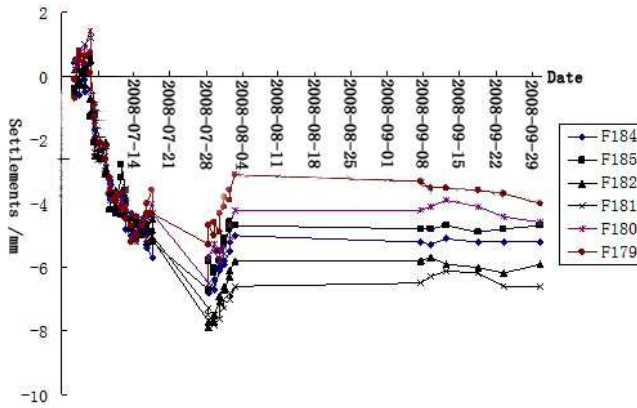


Figure 5 Typical curves of these settlements of these houses

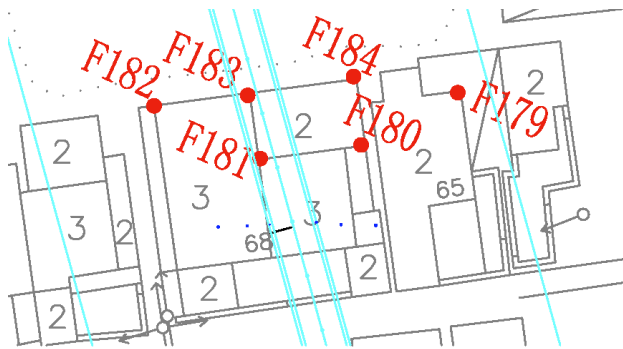


Figure 6 Positions of measuring points F179~F184

As it is shown, the typical longitudinal settlement curve (Figure 7) of the ground during pipe-jacking can be divided into 4 stages, including fluctuation stage, uplift stage, settlement during construction and settlement after construction.

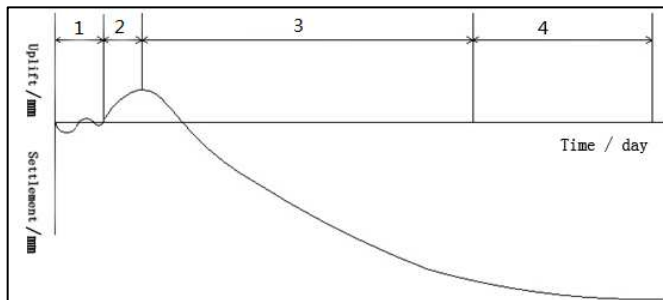


Figure 7 Longitudinal settlement curve of pipe-jacking

(1) Fluctuation stage

When the pipe-jacking machine head is 100m away from the measuring point, it is known from the measured data that measuring point will have small fluctuation up and down. The normal pipe-jacking speed is 15m/d, and this stage begins about 1 week before the machine arrives the measuring point. The range of the settlement of the stage is -2~1 mm.

(2) Uplift stage

As the pipe-jacking machine head approaches the measuring point, the measuring point will rise obviously. This stage begins when the machine head is about 50m away from measuring point, namely 3 days before the machine arrives the measuring point. The range of the settlement of the stage is 0~5mm.

(3) Settlement during construction

When the pipe-jacking machine arrives near the measuring point, the uplift of the point gets the maximum value. Then the point

Table 3 Stage settlement control standard (mm)

Level	Fluctuation stage	Uplift Stage	Settlement during construction	
			Part a	Part b
I	-1~+1	0~+2	0~-4	0~-1
II	-2~+1	0~+3	0~-6	0~-2
III	-4~+1	0~+4	0~-10	0~-5
IV	-5~+1	0~+6	0~-15	0~-10

Where, the value is incremental value not the accumulated value.
Level I and II are levels of micro-disturbance.

During pipe-jacking construction, the settlement of the ground and surface structures must be carefully measured, so as to control the stage settlement according to the standard above. And in this way micro-disturb pipe-jacking is satisfied.

4. TECHNOLOGIES OF MICRO-DISTURBANCE PIPE-JACKING

4.1 Stabilization of the excavation surface

There are two ways to keep the stabilization of the excavation face during pipe-jacking construction. One is to keep the balance of the pressures of soil and pipe-jacking cutter head. The other is to control the speed of slurry discharging.

The field measuring has shown that the front supporting force decided the degree and scope of the soil disturbance. In theory, if the front supporting force is equal to the natural soil pressure, the soil will have no loss and disturbance, and the settlement on the ground is zero. But in fact, this ideal balance cannot be satisfied. If the front supporting force increases, the front soil will be extruded heavily, and the ground above will uplift. If the front supporting force decreases too much, the soil will have stress relief and the ground above will have settlement. So the pipe-jacking working port pressure should be properly set, so as to control the balance of the pressure.

To control the pipe-jacking cutter head pressure, firstly the preliminary pressure should be set according to the situation of the soil layer. Secondly combining the soil pressure change measured by the sensors, the pipe-jacking working port pressure is tuned in the way of controlling disposing soil speed.

In the pipe-jacking part of Beijing West Road – Huaxia West Road Power Cable Tunnel, the construction company Shanghai No.2 Municipal Engineering Co., Ltd developed slurry pipe-jacking machine with very big cutter head. This kind of machine can limit the loss of the soil to the minimum value (about 3%).

This machine used 6 inch slurry channel instead of traditional 4 inch slurry channel. The pump device is correspondingly improved to expand the slurry flow, and it is a non-blockage grit pump device. On account of the stiff clay, a high-pressure water line is added to the slurry channel to crush the stiff clay and other impurity. This improvement insured the sufficiently effective slurry channel to control the pressure of the supporting force, namely the disturbance of the soil.

The machine is also equipped with PLC (programmable calculator) to realize the automatically pressure balance. During excavation the pressure can be adjusted by controlling the slurry flow. When the excavation paused, the pressure can be adjusted by injecting slurry to the excavation face. The excavation surface can be stable all the time.

4.2 Control of the pipe-jacking speed

The choice of pipe-jacking speed should let the soil be cut instead of being extruded. Excessive extruding is bound to arouse the pressure difference, and the disturbance increases. Normally the advancing

speed should be limited to 20~30mm/min, apparently the advancing speed is different in different geology condition. The key point is to make the soil quantity into the port equal to the soil quantity out of the port. Besides controlling machine port pressure reasonably, the controlling of the advancing speed is also very important. If the pipe-jacking machine advances too fast, the rotating speed of the spiral transportation machine goes to the extreme value, which will cause failure of pressure control. So the highest advancing speed should be determined according to the spiral transportation machine. The soil pressure changes frequently. The excavated soil quantity and the pipe-jacking speed should be adjusted accordingly to make the soil disturbance small.

In this project, the pipe-jacking speed always changes properly according to the geological conditions to satisfy the micro-disturbance construction. The advancing speed during underpassing Huangpu River is shown in Figure 8.

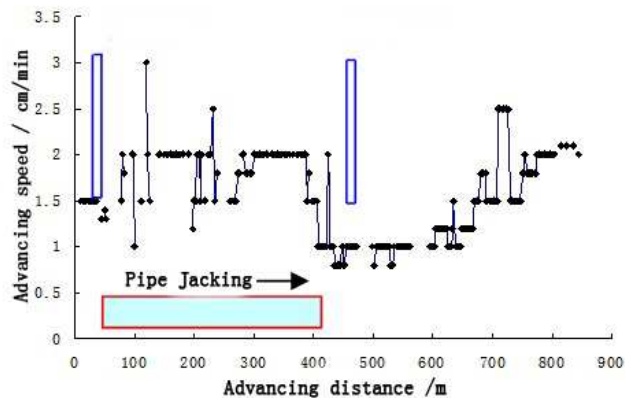


Figure 8 Advancing speed during underpassing Huangpu River

When the pipe-jacking machine leaves the working shaft about 42m, the machine begins to underpass flood wall east of Huangpu River at the speed of 15mm/min, a little slower than the speed at 20mm/min when the machine underpass Huangpu River. Then during the time when the machine underpass the flood wall west of Huangpu River, because of various obstacles the speed slows to 10mm/min. Much time is used to dredging the slurry line and to strengthening injecting slurry to decrease the disturbance to the soil layer.

4.3 Sludge lubricating sleeve technologies

Thixotropic slurry fulfilled the space about 2~5cm thick between soil and the pipe, which forms an imperviable area. The slurry stabilizes and provides the soil in case the soil collapses. Besides, the slurry decreases the friction force to insure the pipe-jacking safe and efficient.

Bentonite slurry is the most economic and effective slurry in pipe-jacking construction. Thixotropy of the bentonite slurry comes from its special mineral structure. The micro-disturbance pipe-jacking requires higher standard of the sludge lubricating sleeve.

To form an effective imperviable sludge lubricating sleeve, reduce the friction force and stabilize the tunnel soil, the slurry must have excellent characteristics such as good shear thinning behaviour, good thixotropy, enough gel strength and suitable solid particle distribution corresponding to the geological condition.

Good shear thinning behaviour makes the slurry flow smoothly to form an effective sludge lubricating sleeve.

Good thixotropy is helpful for the slurry to cement soil particles quickly during permeation. The permeation distance is shortened and the imperviable sludge lubricating sleeve is formed quickly.

Enough gel strength is good to increase the soil particle strength. But the too high gel strength will reduce the fluidity of the slurry

which will go against the slurry injecting and will increase the advancing resistance.

According to the practice of field construction, the characteristics of the bentonite slurry should be limited as the following.

Apparent viscosity: 12~20mPa·s

Shear dilution index>10

Gel strength: 3~10Pa

Thixotropy>1Pa

Filter loss<15ml

For high porosity gravel and quicksand layer, besides the above requirements, the slurry must have high solid content and certain particle size distribution to fulfil the space of the soil layer, reduce the loss of the slurry and to control the distance of the slurry. So the thixotropy slurry must have the proper particle size distribution corresponding to the geological conditions.

The control of thixotropy slurry of ground settlement was studied through the indoor model experience. There are four experience conditions (1. no slurry injecting; 2. tradition slurry injecting 1; 3. tradition slurry injecting 2; 4. optimized slurry injecting). Ground settlements change with the jacking distance (Figure 9). Take the point S-3 for example, the settlement of tradition slurry injecting 1 is 68% less than the condition of no slurry injecting, tradition slurry injecting 2 is 63% less and the condition of optimized slurry injecting is 75% less.

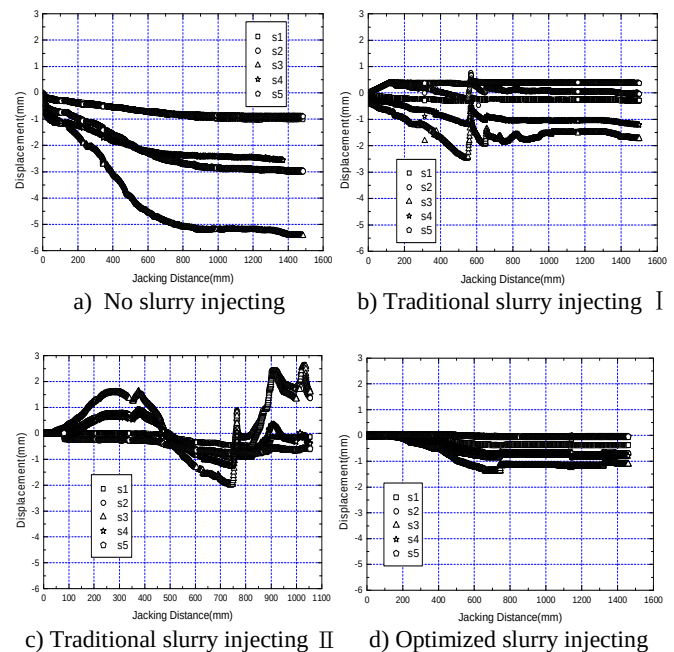


Figure 9 Ground settlements changing with the advancing distance of 4 conditions

In this project, the excellent and complete sludge lubricating sleeve is formed around the pipe-jacking machine to reduce the disturbance to the soil layer.

4.4 Attitude control

The pipe-jacking machine deviation is bound to cause the soil's displacement, and the greater is the deviation, the greater is the extruding to the soil. The deviation will form a gap which needs to be fulfilled with the soil above. The big deviation should be avoided during pipe-jacking construction.

Improving the precision does help to avoid the big deviation. Being anxious to control the attitude may cause the excessive high pressure of the pipe line flank and leakage owing to the break of pipe line and the soil disturbance increases meantime.

In practice attitude control, the three principles “control constantly, control lightly, and control timely” should be followed.

“Control constantly” means that the attitude should be controlled in time instead of waiting till the deviation is too big.

“Control lightly” means that the attitude control should be lightly instead of heavily, which will cause the attitude control curve to be steep. And this will bring difficult to the next attitude control.

“Control timely” means that when the deviation decrease to a proper value, the attitude control hydro-cylinder should be return to zero.

There is no corresponding study about the pipe-jacking attitude control standard home and abroad by now. But from the practice construction, we know that the deviation must be limited to a certain range during pipe-jacking. So according to the pipe-jacking deviation statistics of the four part (about 4.3 km long totally) of the Expo Power Cable Tunnel in Shanghai, the pipe-jacking attitude control standard is put up tentatively.

Table 4 shows the situation of the vertical deviation of the pipe-jacking machine. And table 5 shows the situation of the vertical deviation. The first column means the interval of deviation. The second column means the times of deviation in the corresponding interval. The third column is the proportion of each interval's time. The forth column is the accumulated proportion.

Table 4 Vertical attitude statistics

Deviation(cm)	The times of interval	Interval proportion	Accumulated proportion
0	141	23.81%	23.81%
1	163	27.53%	51.35%
2	135	22.80%	74.15%
3	101	17.06%	91.21%
4	34	5.743%	96.95%
5	10	1.68%	98.64%
6	4	0.67%	99.32%
7	0	0.00%	99.32%
8	0	0.00%	99.32%
9	4	0.67%	100.00%
10	0	0%	100.00%

Table 5 Horizontal attitude statistics

Deviation(cm)	The times of interval	Interval proportion	Accumulated proportion
0	107	18.13%	18.13%
1	93	15.76%	33.89%
2	92	15.59%	49.49%
3	111	18.81%	68.30%
4	125	21.18%	89.49%
5	32	5.42%	94.91%
6	18	3.05%	97.96%
7	0	0.00%	97.96%
8	2	0.33%	98.30%
9	0	0.00%	98.30%
10	1	0.16%	98.47%
11	2	0.33%	98.81%
12	1	0.16%	98.98%
13	6	1.01%	100.00%
14	0	0.00%	100.00%

This project is a good example of micro-disturbance pipe-jacking. The statistics from it can be used to study the attitude control of the pipe-jacking. If the failure probability is set to 1%, the vertical deviation should be controlled within 55mm; the horizontal deviation should be controlled within 120mm. If the failure probability is set to 3%, the vertical deviation should be controlled within 40mm; the horizontal deviation should be controlled within 55mm. If the failure probability is set to 5%, the vertical deviation should be controlled within 36mm; the horizontal deviation should be controlled within 50mm.

4.5 Timely slurry replacement

The soil layer loss and the disturbance around are main reasons of ground settlements. Different soils of different physics properties have different settlements.

After construction the total load of the soil decreases because of the disappearance of the construction. The elastic deformation is recovered, while the plastic deformation remained. So the bentonite slurry should be replaced timely after construction to increase the yield stress to reduce the plastic deformation of the soil. In places where the underground water abound or the soil is loose, measures of improving soil properties such as slurry injecting, deep stirring and dewatering will reduce the consolidation settlement after construction to protect the environment. The slurry replacement can be compounded with cement, fly ash and bentonite etc. The slurry replacement should have a long initial setting time and good pump ability; the strength after setting should be higher.

The pressure and the quantity should be controlled properly. If the injection pressure is too great, the soil around the pipe line will be extruded to outside, and the ground will uplift. If the injection pressure is too low, the soil move inside, and the ground will have settlement. The proper injection pressure should be 1.1 to 1.2 times of static earth pressure. And the injection slurry quantity should be 140% to 200% of the theoretical quantity. The slurry replacement is an effective way to control the ground settlement after construction.

5. CONCLUSION

Before construction, proper circuit should be planned to avoid too curved line and suitable equipment should be chosen. During pipe-jacking, the stability of the excavation, proper advancing speed, and good sludge lubricating sleeve, attitude control, and timely slurry replacement should be assured. And combining with auxiliary construction methods such as freezing and dewatering, the pipe-jacking can also limited the disturbance to the millimetre level.

In part 6#~7# of Shanghai Beijing West Road – Huaxia West Road Power Cable Tunnel, the jacking pipe underpasses Huangpu River and its flood wall through power sand layer with artesian water and sandy silt layer. With adopting the technologies introduced above, the pipe-jacking project was finished successfully. All the settlements were less than 20 mm, and no accidents such as percolating water happened.

In part 12#~13#, where the pipe-jacking machine underpasses lots of old houses, all the settlements were limited within 15 mm. No destruction of houses happened and the pipe-jacking project was finished without influence on the normal life of local residents.

The successful micro-disturbance construction of the pipe-jacking part of Shanghai Expo Power Cable Tunnel provides good experience and reference to the future similar project.

6. ACKNOWLEDGEMENT

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