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A New Technique and Its Application in the Conservation of Historical Masonry Constructions
——underpinning by manual pipe-jacking

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Abstract: The structural damages, which result from the inadequate bearing capacity or the asymmetric support of foundation, are one of the crucial works in the conservation of historical masonry constructions. Firstly ,the box girders are slowly and evenly jacked by the manual pipe jacking technique ,and then casting the core beam to form a whole, so the construction is gradually situated on a "tray" with sufficient rigidity. Consequently, the structural damages caused by the inadequate bearing capacity or the asymmetric support of foundation is thoroughly treated. Based on the field test, the principle of the underpinning by manual pipe-jacking , the mutual effect mechanism between box girders and soil, the calculation of jacking force and its influence factors are investigated in detail, and the empirical formula of calculating jacking force is also presented.

Keywords: Historical masonry constructions, pipe-jacking, underpinning

Introduction

Approaches taken to reinforce foundation soil for the historical masonry constructions of China are introduced by the great technical manual of code for construction (Li 2006),the Song dynasty , generally consist of three different methods, including compacting the soil ; improving the quality of the solid by adding some aggregate of the broken Brick and tile or the crushed stone; changing the soil by better one. Especially, the second is widely used in most historical buildings. From the Ming dynasty to the Qing dynasty, lime soil develops gradually as the most popular material for reinforcing foundation soil. As a result, the load-bearing wall is directly supported by such frail foundation. So the building is extremely sensitive to the differential settlement caused by the inadequate bearing capacity or the asymmetric support of foundation, especially, for the historical masonry constructions. Underpinning by manual pipe-jacking, Therefore, forming a larger stiffness underpan by underpinning, is the basic work to cope with such structure disease of ancient masonry buildings.

Comparison with traditional pipe-jacking technology，underpinning by the rectangular pipe jacking technology in masonry constructions has four salient characteristics: ① the section shape of jacking pipe is rectangular, rather than the usual circular. ② the box girders are directly jacking under the upper structure, the thickness of the soil between box girders and upper structure is thin, so not considering the "arch action" (An et al. 2002). ③ the settlement produced in the process of underpinning, is the main reasons for buildind up stresses and strains in the upper structure,and has a direct and significant impact on its safety. ④ the box girders are usually jacked through backfill soil or rammed earth, so the geological conditions are relatively single,but the differences along the thickness of soil are often remarkable, therefore,the interaction between box girders and surrounding soil is more complex.

The technique has been successfully used in some engineering of the conservation of historical masonry construction yet (Zhang et al. 2009, Xian et al. 2005), it is shown that this process has advantages in the field of masonry protection, but the basic problems involved in the process have not been studied yet. Based on a practical engineering, the basic principles of the technique, the process of jacking and the calculation of jacking force are introduced in this paper, it may be benefit to the further study for this new structure protection technique.

Basic Process

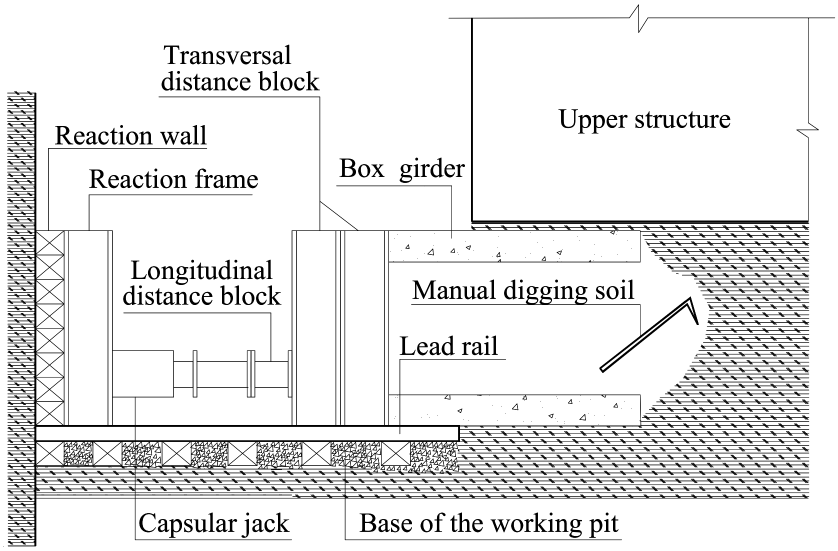


Figure 1: *Process of the box girder jacking*

As a special technology for the conservation of historical masonry construction, underpinning by manual pipe-jacking come from the trenchless technology (Gang 1997), which is widely used in tunnel, municipal engineering etc. The basic construction principles are described below: Firstly, digging in the front of box girders, and box girders are slowly and evenly jacked under the bearing wall of upper structure by capsular jack simultaneously, then casting the core beam to form a whole, so upper structure is gradually situated on a "tray" with sufficient rigidity. Combine with the jacked piles, such structure disease is thoroughly solved, and it uttermost reduces the damage in the process of reinforcement protection.

The main process may be summarized as follows:

(1) Prefabricating the reinforced concrete box girders.

(2) Digging working pit, lay the basis, adjust the lead rail, lay the reaction wall and reaction frame, adjust the jacking system to work together.

(3) Digging soil in the front of box girder, open the capsular jack to jack box girders when digging some space, and so forth box girders are jacked under the bearing walls one by one. Figs. 1, 2 show the jacking system and a practical engineering instance respectively.

(4) After jacking all box girders, the pavilion is finally situated on the box girders. Then excavating soil around box girders, lay steel bars within box girders, and finally pouring concrete to form a “tray” with enough stiffness.

Thus, making the original structure situated on a reinforced concrete rigid platform, greatly enhance the structure resistance to differential settlement, but also enhance the safety of underpinning, correction, lifting, and translation.

Design for the Box Girders

As transitional elements in the process of underpinning using pipe jacking technology, box girders bear upper structure loads during the construction period, they also be used as internal core beam’s template after construction, their design factors should meet the strength demand under all kinds of loads , some special construction conditions. The key influencing factors can be summarized as follows:

(1) Load problem. Jacking process determines the size and the imposed means of the site loads, especially the eccentric concentrated force caused by the inevitable correction, correction measures or the reaction wall deformation,is key role in the design for box girders.

(2) Size of box girder. Taking into account the space requirements during construction, interior clear height and width of box girder should be not less than 800mm, 400mm respectively.

Jacking System and Facilities

The jacking facilities of manual pipe jacking generally refer to the temporary facilities on the site during construction, including working pit, reaction wall, lead rail and foundation. Jacking system refers to the jacking equipments, for instance, capsular jack, jacking iron, padding block, soil transporter, hoisting facilities, error monitoring and correction equipment.

Working Pit The shape of working pit is commonly rectangular, the plane size of its bottom , generally is determined by the size of box girder, jacking technology, jacking equipment systems, groundwater table and soil behaviour, working space, mode of transportation and so on.

① Length of working pit. The length of the working pit have relations with many factors ,for instance, the maximum length of box girder, the length of capsular jack, reaction frame, the thickness of single jacking frame, the thickness of the square timber installed at the reaction wall , mode of soil transportation and so on (Fig. 1). The length of the working pit can be calculated as follows:

$$L = L_1 + L_2 + L_3 + L_4 + L_5 + S_1 + S_2 \quad (1)$$

Where: L-the length of the working pit (mm);L_1-the length of the longest box girder (mm); L_2-capsular jack(mm); L_3-the thickness of single jacking frame (mm); L_4-the thickness of the reaction frame(mm); L_5- the thickness of the square timber installed at the reaction wall (mm), generally preferable to 250mm; S_1-the length of previous box girder left on the lead rail (mm); S_2- the reserved length of box girder considering soil transportation.

It can also be estimated through the following formula:

$$L \geq L_1 + 1600 \quad (2)$$

② Width of working pit. The width of working pit can be commonly calculated used the following formula:

$$B = B_1 + 2b + c \quad (3)$$

Where: B- the width of the working pit (mm); B_1- the width of the box girders (mm); b-the size of two sides working space (mm); c- the space required for the support and the lead rail (mm).

It can also be estimated through the following formula:

$$B \geq B_1 + 1600 \quad (4)$$

Foundation and Lead Rail Fig. 1 shows the schematic of the working pit.Working through practical field experiments, it shows that when weight of a single box girder is no more than 30kN, the working pit can be constructed as the following steps: lay the gravel underlayer at the bottom of the working pit, then put square timbers on the underlayer, after leveling according to the design point, install the lead rail welded by I-section steel. Fig. 3 shows the schematic of the working pit. Compared to the traditional concrete underlayer, it has some advantages, for example, the construction time is shorter, materials can be repeatedly used, the construction is simpler, if necessary, it can adjust the elevation easily.

Reaction Force System Unlike traditional pipe jacking, when underpinning applying the pipe jacking technology in masonry constructions, the general depth of working pit is not more than 5000mm, the capsular jack applies force to the square timbers through the reaction frame, the square timbers can spread the action area of the anti-force (Fig. 1), and also directly act on the reaction wall.The basic requirements of the reaction wall can be summarized as follows:

① Stiffness. Acted upon by the capsular jack's anti-force, material of the reaction wall and the soil have a greater experience of deformation. Jack will be consequent to offset the effective stroke and reduce the efficiency of jacking. The larger deformation make the original flat reaction wall to tilt, consequently, generate eccentric effect and produce an additional moment of couple , cause the jacking error, even give rise to quality and safety incidents.

② Strength. It should avoid too much distortion or compression to damage jacking system, which may cause a larger margin of error, even an accident. The calculation of the strength of the reaction wall should fully consider the possible maximum jacking force, the adverse eccentricity effect due to the correction, as well as the uneven force caused by the deformation of the square timber; ensure that it has a certain degree of security reserve.

③ Simple in structure, material uniformity, easy disassembly. As a temporary structure system, the reaction frame is commonly made by steel on site, the back of the reaction is mostly builded by uniform square timber, in order to avoid deformation due to using inconformity materials.

Calculation of the Reaction Wall Literature (Yan and Jiang 2005) gives the experience formula for calculating the reaction wall, the author confirmed the usefulness of this formula through the design of an actual project (Zhang et al. 2009).The reaction wall bear all resistance during construction, so it should have sufficient stability:

$$F_c = K_r \times B_0 \times H \times \left(h + H/2\right) \gamma \times K_p \quad (5)$$

Where: F_c-the carrying capacity of the reaction wall(kN); B_0-the width of the reaction wall (m); H-the height of the reaction wall(m); h-the height of the top of the reaction wall to ground (m) ; γ -the soil bulk density (kN/m3); K_p- the coefficient of passive earth pressure, it is related to the internal friction angle of soil,its calculation formula is as follows : $K_p = \tan^2(45° + \phi/2)$;K_r- the soil resistance coefficient of the reaction wall; when the depth is shallow, the wall is directly contacted with the soil, $K_r = 0.85$;when requiring driving into the steel sheet pile, $K_r = 0.9 + 5h/H$.

Calculation of the Jacking Force

In the jacking process, the jacking force should overcome the friction, the front-end resistance of the first box girder, while influenced by various external factors, such as correction, the displacement of the reaction wall and so on. Accurately estimating the jacking force determines the design for jacking equipment, anti-force systems, the box girders.

The situ test results during jacking course and the theoretical analysis show that the main jacking resistance includes four components: (1) the front-end resistance of the first box girder; (2) the friction between the the box girders and soil induced by weight of the upper structure; (3) the friction between the box girders and soil induced by weight of the box girders; (4) the friction induced by the soil cohesion between the box girders and the soil.

To simplify the calculations, this paper adopts the following basic assumptions: (1) the box girders are close contact with the surrounding soil, seamless. (2) the friction coefficient between the box girders and surrounding soil is constant.

Front-end Resistance of the First Box Girder In order to reduce stratum loss caused the gap around the box girders, there is always "less digging"in practical engineering, so the face resistance can not be ignored. Taking into account the cross-section characteristics of the box girders and the amount of "less digging", the existing empirical formula (Yu and Chen 1998) is amended to:

$$F_0 = A_0 pN \qquad A_0 = 2(b+h)t \quad (6)$$

Where: b- the width of the box girders (m); h- the height of the box girders (m); t- the thickness of "less digging" soil (m), with the value 1/2 of the wall thickness of the box girders; A_0-the "less digging" area (m^2); p- the earth pressure induced by the weight of the upper structure (kN/m^2), without considering the influence of the reserved soil between the box girders and the upper structure, N-the coefficient of penetration resistance (Yu and Chen 1998), take 1.0 in ordinary clay , take 1.5 in the sand and take 3.0 in hard soil. When underpinning by the manual pipe jacking technology in masonry constructions, its foundations is extremely hard due to the perennial press of the upper structure.

Table 1 gives the four sets of field measured values, and also compared with the relevant standards (Code for construction technology and acceptance of pipe jacking), literature (Yu and Chen 1998), the paper's formula. The results show that the paper's formul is closer to the measured values, the recommended formula in norms and literature (Yu and Chen 1998) for circular pipe jacking is not applicable for the process.

Table 1： comparison with the resistance of the first box-section beam between computation and testing

Field test(kN)				standard formula [9]	empirical formula [8]	The paper's formula
314	251	188	251	126	199	277

Friction Induced by Weight of the Upper Structure and the Box Girders The establishment of this assumption makes the equation (7) rather clear in the physical meaning .However, the actual observations show that the error caused by this simplification increases with the increase of the distance L.,which can be explained by the mechanism between the box girders and the soil.

$$F_1 = \mu 2bLp \qquad F_2 = \mu WL \tag{7}$$

Where: F_1-the friction resistance between the top and bottom of the box girders and the soil (kN); F_2 – the friction between the box girders and the soil caused by weight of the box girders (kN); L- the jacking length (m); p- the earth pressure induced by the weight of the upper structure (kN/m^2) ; μ - the friction coefficient between the box girders and the soil, its values was given by $\mu = \tan\frac{\varphi}{2}$ in the literature (Yu and Chen 1998) (φ -the internal friction angle), National standards (Code for construction technology and acceptance of pipe jacking) also listed the empirical value of the friction coefficient between the concrete pipe and the soil.

Friction Induced by the Soil Cohesion Between the Box Girders and the Soil Measurement shows that the skeleton structure of a certain thickness of the soil around the box girders is constantly destroyed and reorganized, the friction induced by the soil cohesion between the box girders and the soil increases with the increase of jacking distance,but its increasing trend is gradually slow,and it is an important component of the jacking resistance. When assuming that the soil cohesive is uniformly distributed along the outer surface of the box girders ,it can be expressed as:

$$F_3 = \mu 2(b+h)CL \tag{8}$$

Where: F_3-the friction induced by the soil cohesion between the box girders and the soil (kN); C- the adhesion force between the box girders and the soil (kPa); other parameters ibid.

Other Factors Affecting the Jacking force Other factors obviously affecting the jacking force are as follow:① the construction interval. ② the stiffness of the reaction frame the reaction system. Due to the inevitable deformation of the reaction system, the practical direction of the jacking force deviates from its original designed direction, which changing the distribution of the friction among the box girders, then influencing the jacking force. ③ error correction. The inevitable corrective action, often change the distribution of the power of the capsular jacks, resulting in the increase of the power of some of the capsular jacks.

Considering all these factors, the calculation formula of the jacking force can be expressed as:

$$F = k\left\{\ 2(b+h)tpN + \mu\left[2bp + W + 2(b+h)C\right]L\ \right\} \tag{9}$$

Where: k -safety factor, the selection of the safety factors is mainly take into account other factors that are not considered in this paper.as well as the simplifying assumptions, which may make the calculated value too small, this article suggests values of 1.2.

A Case Study

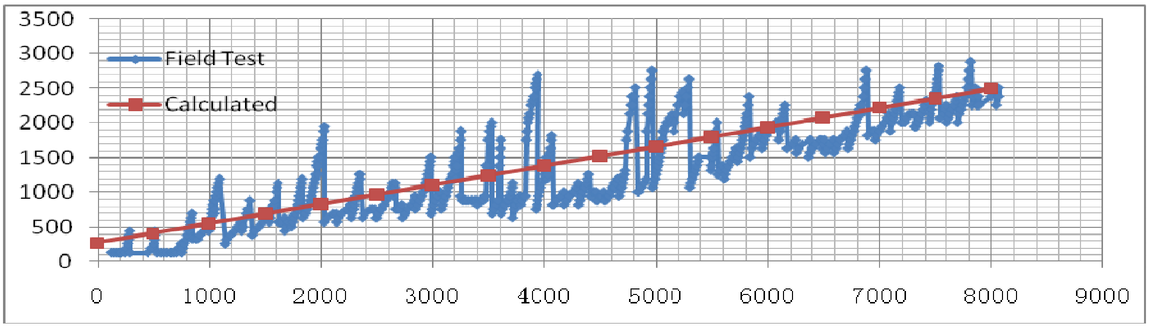
According to a practical underpinning for a masonry structure in the Yuan Dynasty[3], the design for the box girders, the jacking process, comparison the calculation of the jacking force with the field test. the base of the project was made by the silty clay mixing brickbat through compacting layer by layer.

The jacking distance is 8100mm, the thickness of the reserved soil between box girders and upper structure is 400mm . The basic parameters of the upper structure, the jacking technology, equipments, geotechnical parameters can be found in the literature (Zhang 2009) for details. The main technical parameters are listed here, with a view to benefit similar projects.

Design for the Box Girders The size of the main precast concrete box girders adopted in the project is 1600 × 1200 × 1300 × 180mm (length×width×height × thickness), the size of their middle holes is 1240mm × 840mm(width × height).

Design for the Jacking System According to the calculation, the capsular jacks used the system of "a pump double support", the reaction frame and the jacking frame were both made by steel. The working pit was constructed as the following steps: lay the gravel underlayer at the bottom of the working pit , then put square timbers on the underlayer. The lead rail was welded by angle steel and I-section steel (Fig.2). The jacking system, is easily constructed, easy to adjust, easy to correct, and can be repeatedly used.

Calculation of the Jacking Force Fig. 3 shows the calculated and the field test curve of the jacking force, the two results are approximately coincided.



Annotation:longitudina axis represent jaking-force, horizontal axis represent distance

Figure 2: relationship between jacking force and distance

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