Design of Municipal Sewer Pipe Jacking under Complex Geological Conditions in Plateau Regions

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Abstract: The drainage and sewage interception project in Zhaoyang District involved the installation of a DN1000 municipal sewer pipeline with a total length of 1541 m. Considering factors such as geological conditions, pipe diameter, buried depth, groundwater level, as well as the impact of nearby underground and aboveground structures and traffic, the trenchless construction method of pipe jacking was selected for implementation. The pipeline followed the route of Weiba Road, crossed Jinying Avenue, and then proceeded along the Second Ring East Road until it reached the bank of Yaowan River. The project design took into account practical considerations, including the sewer pipe diameter, material selection, pipeline routing, construction of pipe jacking starting shafts, and the design and modification of arriving shafts, in line with the specific engineering requirements.

1 Introduction

With the accelerated process of urbanization, the urban population is continuously increasing, leading to a gradual rise in sewage discharge. Therefore, the proper functioning of sewage pipelines is crucial for urban development. Serving as the passageway for discharging wastewater, sewage pipelines are integral components of municipal road projects. The construction of sewage pipelines directly impacts the environmental hygiene and safety of the city, making it a vital element in water environmental protection.

The construction method of sewage pipelines should be determined based on factors such as geological conditions, pipe diameter, buried depth, groundwater level, proximity to underground and aboveground structures, and traffic impact. After conducting a technical and economic comparison, the choice between methods such as trenching, jacking, or shield tunneling can be made (Meng et al., 2016), (Zhang et al., 2013), (Zhou et al., 2012), (Meng et al., 2016).

The construction of sewage pipelines can be influenced by various factors, each requiring different demands on construction personnel and equipment. These factors can have a direct impact on the construction quality, safety, progress, and costs of the project. Trenching and non-trenching construction are the two common methods for sewage pipeline construction. Pipe jacking is one of the trenchless construction methods, widely used in densely populated and heavily trafficked places, as well as in the construction and maintenance of urban underground pipelines crossing highways, railways, and rivers (Shimada et al., 2023), (Sterling R.L. , 2020). It has the advantages of safety, reliable quality, environmental friendliness, strong stratum adaptability, and high efficiency (De la Fuente et al., 2022). Therefore, it is widely used in municipal sewage pipeline construction, with the capacity of meeting relevant requirements. However, this construction method has high technical requirements, and can be significantly influenced by groundwater levels, soil conditions, and pipe diameter. Thus, a scientific and rational selection and application of jacking technology is necessary to ensure the successful construction of municipal sewage pipelines.

2 Project overview

The drainage and sewage interception project in Zhaoyang District aims to address the sewage discharge issue in the eastern part of Zone 24, Zhaotong City. Zone 24 is a newly developed resettlement area that is currently in the final stages of completion. Weiba Road is located on the south side of this area and is currently under construction. It connects Tengfei Road and Jinying Avenue, serving as a primary municipal road extending northward from the Second Ring East Road and acting as a main entrance and exit for Zone 24. Weiba Road has a total planned length of 1727 m, with a road red line width of 24 m. According to the plan and the actual terrain, Weiba Road is designed with higher elevations at both ends (Tengfei Road and Jinying Avenue) and a lower elevation in the middle, with the lowest point at the intersection of Weiba Road and Xianghe Road, which is 5 m lower than the junction with Jinying Avenue. The road adopts a rainwater and sewage diversion system, with DN500 sewage pipes installed on the north side.

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However, the currently implemented sewage pipes on Jinying Avenue and Tengfei Road are designed to discharge sewage into Xianghe Road, and there is no outlet for the sewage collected in Xianghe Road. Due to ongoing construction, the sewage from Zone 24 has not been generated and it has not affected residents' daily life.

Zone 24 is a densely populated area with a planned residential population of 60,000. Currently, the construction of underground infrastructure for water supply and drainage has been completed in this area. While rainwater naturally flows into a small river situated in the low-lying eastern part, the absence of municipal sewage interception pipes hinders the connection of sewage. Upon the population's arrival in the area this year, the sewage generated is discharged directly into the river, causing significant pollution to the downstream urban sections of Yaowan River and Tuwei River. Hence, the immediate implementation of a sewage interception project in this area is essential, as shown in Figure 1.

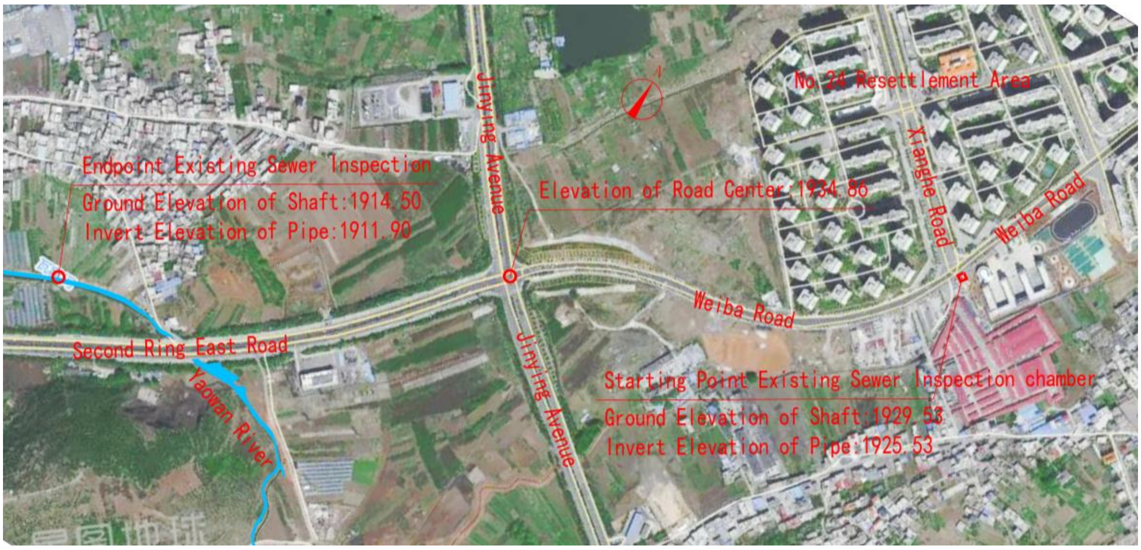

Figure 1. Project profile diagram

Following the on-site investigation, it was discovered that the sewage interception main pipe in this project has only one sewage discharge outlet, located along the Yaowan River. Presently, the ground elevation of the sewage inspection chamber at the upstream intersection of Weiba Road and Xianghe Road is 1929.53 m, with an invert elevation of 1925.53 m. The sewage is connected to a DN500 reinforced concrete sewage pipe buried at a depth of 4 m. The ground elevation of the sewage inspection chamber at the downstream is 1914.50 m, with an invert elevation of 1911.90 m, and a buried depth of 2.60 m. The height difference between the upstream and downstream sewage inspection chambers is 13.63 m. The sewage pipe is laid along the Weiba Road to Second Ring East Road, with a length of 1541 m. Gravitational drainage of sewage is feasible, but the buried depth at the intersection with Jinying Avenue is 11.10 m. The sewage pipe is laid along the Weiba Road to Second Ring East Road, with a length of 1541 m. Gravity discharge of sewage is feasible, but the buried depth at the intersection with Jinying Avenue is 11.10 m.

Presently, the road construction of Weiba Road is in its final stages of completion. Weiba Road is accompanied by buildings, retaining walls, and other structures, whereas Second Ring East Road is flanked by green areas and an array of underground pipelines. Therefore, adopting the traditional mass excavation method would potentially damage the road surfaces of Weiba Road and Second Ring East Road. Additionally, due to the considerable buried depth of the pipelines, the construction difficulty is substantial. After comparing the technical and economic factors, the more mature pipe jacking method was chosen. The pipeline was designed accordingly for pipe jacking, with a total length of 1417 m. For the end segment along the Yaowan River, slotted construction was used with a length of 124 m.

3 Geomorphology and geology overview

3.1 Geomorphology overview

Zhaoyang District is located in the Yunnan-Guizhou Plateau, a typical karst landscape area. The original site was a sloping terrain, which has been largely leveled during the construction of Weiba Road. The overall terrain is high in the northeast and low in the southwest, with a slope ranging from 3 to 5 degrees. The geomorphology is characterized as a foothill slope edge accumulation geomorphology unit, resulting in a relatively flat overall terrain across the entire site.

3.2 Geology overview

According to the geological investigation report, the proposed construction project has a significance level of Grade 2. Both the site complexity and foundation complexity are classified as Grade 2. The regional crustal stability of the proposed construction area is categorized as relatively stable (III_1). After implementing appropriate engineering measures, the site is considered generally suitable for construction, falling under the category of anisotropic foundation. The soil type of the proposed site is classified as medium-soft site soil, and the construction site category is CAT-I.

The exposed effective geological structure within the excavation control lines of the site is as follows: (1) Layer of top plate with miscellaneous fill, with a buried depth of 0.00 m and a thickness ranging from 1.00 m to 3.40 m; (2) Layer of clay with a buried depth ranging from 1.00 m to 2.50 m, which was not fully exposed in this investigation with an exposed thickness of 7.20 m to 13.10 m; (3) Layer of round gravel with a buried depth ranging from 2.60 m to 3.40 m, and a thickness of 3.10 m to 4.20 m; (4) Layer of clay with a buried depth ranging from 5.80 m to 13.60 m, not fully exposed with an exposed thickness of 0.80 m to 14.40 m; (5) Layer of silty clay with a buried depth ranging from 1.00 m to 1.60 m, and a thickness of 4.70 m to 5.90 m; (6) Layer of gravel with a top depth ranging from 6.10 m to 7.30 m, not fully exposed in this investigation, with an exposed thickness of 2.80 m to 14.10 m. Based on the onsite excavation and sampling conditions, there was an approximately 200 m long rock layer composed of hard granite in the middle of the pipeline, posing considerable excavation challenges.

The engineering site is far from the regional active fault, with no active fault passing through it. Seismogenic faults are absent within a 10-kilometer radius, so the near-field effects of seismic parameters can be disregarded. The site has a seismic fortification intensity of 7 degrees, with a design basic acceleration of ground motion set at 0.10 g and a seismic response spectrum characteristic period of 0.45s. design earthquake group is Group 3. The design earthquake group is classified as Group 3. As a result of its location in a region with unfavorable seismic conditions, the building construction falls under the standard fortification class, referred to as Class C.

The groundwater level within the site experiences relatively significant variations. Water levels were not observed at exploration points ZK6 to ZK19, while in the remaining boreholes, the water level depths range from 2.80 to 5.60 m, with an average depth of 3.88 m. The elevation of the groundwater level varies between 1910.30 to 1227.40 m. The groundwater is mainly present in layers 3 (round gravel) and 6 (gravel), and it is distributed throughout the upper and lower sections of the entire site.

No soft soil, saturated sandy soil, or silty soil was exposed within the exploration depth range of the proposed site.

4 Engineering design key points

4.1 Design and calculation of sewer interception pipeline

(1) Sewage flow prediction

According to the planned population of 60,000 people in the No. 24 resettlement area, the water consumption is estimated at 150 L/person•d, resulting in a total water consumption of 9,000 m³/d. Considering a sewage conversion rate and collection rate of 90%, the total sewage flow in the area is estimated to be 7,290 m³/d, equivalent to 84.375 L/s. With a total variation coefficient of 1.65, the designed peak sewage flow rate is 139.22 L/s (Shanghai Housing and Urban Rural Construction Management Committee, 2021).

(2) Design calculation for sewage interceptor pipe

According to the area plan, the sewage from the No. 24 resettlement area is collected and directed to the existing sewage inspection chamber at the intersection of Weiba Road and Xianghe Road. The diameter of the sewage pipe is DN500. There is one sewage inspection chamber on the left and one on the right of the intersection, and there is no connecting pipe between the two sewage inspection chambers.

Based on the on-site investigation and the drainage plan of Zhaoyang District, the overall drainage direction of the area is towards the west side of the intersection of Erhuan East Road and Yaowan River. The drainage direction is opposite to the longitudinal slope of the road, indicating reverse drainage. The sewage from the existing sewage inspection chamber at the intersection of Weiba Road and Xianghe Road is directed to the existing sewage inspection chamber on the Yaowan River embankment, where a DN1000 sewage interceptor pipe is located. The pipeline is buried at a significant depth, with the deepest inspection chamber reaching nearly 14 m in depth. After multiple discussions and consideration of various options, it has been decided to adopt the jacking method for construction. The specific approach involves constructing a pipe jacking starting shaft at the intersection of Weiba Road and Xianghe Road, where the sewage from the existing inspection chamber is directed. The sewage is guided along Weiba Road and Erhuan East Road through the starting shaft until it reaches the river embankment at the intersection of Yaowan River and Erhuan Road. For safety purposes, a pipe jacking starting shaft or an arriving shaft shall be set up along the route not exceeding 150 m. To reduce excavation difficulties and the depth of the jacking starting shafts, the slope of the sewage pipe should be minimized, with a gradient of 2‰ at the beginning of the project. The pipe jacking method employs reinforced concrete pipes with steel sockets. According to the Hydraulic Calculation Manual, the diameter of the sewage pipe should be DN500 at a flow rate of 139.22 L/s and a flow velocity (V) of 0.91 m/s. Considering construction difficulties and future development in the area, a DN1000 sewage pipe is used for the jacking, with a drainage slope ranging from 1.5‰ to 50‰. Along the route, a total of six starting shafts and 5 arriving shafts are set up. Starting from the 5th pipe jacking arriving shaft at the intersection of Erhuan East Road and Yaowan River, as this section is a dirt road with shallow pipeline burial, the construction method of open-cut excavation is adopted. Subsequently, DN1000 sewage interceptor pipes are laid along the Yaowan River for a length of 124 m and connected to the existing DN1000 sewage pipeline.

4.2 Material election of pipe jacking

Two pipe materials are normally available in the sewage pipeline jacking project: Glass Fiber Reinforced Plastic Mortar Pipe and Reinforced Concrete Pipe. After conducting a comprehensive technical and economic comparison in terms of cost and availability, the selection of reinforced concrete pipe (Grade III) with a wall thickness of 100 mm was deemed suitable. The concrete strength grade of the reinforced concrete pipe is not less than C50, with the impermeability grade in S8. The pipe sections are 2.0 m in length and are interconnected using steel socket joints.

The selected pipe materials are supplied by regular manufacturers and comply with the relevant provisions of "Concrete and Reinforced Concrete Sewer Pipes" (GB/T 11836-2009) and "Reinforced Concrete Sewer Pipes used for Jacking Construction" (JC/T 640-2010) to meet requirements such as pipe strength, appearance quality, dimensional deviation, internal water pressure, and external load resistance (Ministry of Industry and Information Technology of the People's Republic of China, 2010).

4.3 Determination of the sewage pipe jacking routing

The determination of the sewage pipe jacking routing is influenced by the outlet and inlet points in the upstream and downstream sections. The pipeline routing should avoid underground obstacles, and the jacking shafts should also steer clear of existing facilities above ground. Considering the completed construction of Weiba Road and Second Ring East Road, and the existing buildings, roads, green spaces and retaining walls in the surrounding areas, the sewage pipe routing for this project generally followed the existing Weiba Road and Second Ring East Road. Considering that both Weiba Road and Second Ring East Road are already constructed, and the surrounding areas have existing buildings, roads, green spaces, and retaining walls, the sewage pipe alignment for this project generally follows the existing Weiba Road and Second Ring East Road.

4.4 Installation of pipe jacking starting shafts and arriving shafts

The sewage pipe jacking shafts consist of starting shafts and arriving shafts, which are arranged at regular intervals along the pipeline, both in straight sections and at turning points. The placement of these jacking shafts takes into account various factors, including available space on-site, geological conditions, pipeline buried depth, traffic impact, drainage requirements, soil excavation and transportation, local construction techniques, safety considerations, and project investment.

The working and arriving shafts can have different planar shapes, such as circular, rectangular, or square, with circular and rectangular shafts being more commonly used. The choice between circular and rectangular shafts depends on factors like the angle between upstream and downstream pipelines. Rectangular shafts are suitable for straight sections or when the angle between upstream and downstream pipelines is greater than 170°. On the other hand, circular shafts have the advantage of not being limited by the angle between upstream and downstream pipelines, allowing jacking operations in multiple directions within a single shaft.

Given that the sewage pipeline in this project has fewer straight sections and most of the angles between upstream and downstream pipelines are less than 170°, a combination of rectangular and circular starting shafts was adopted. Rectangular starting shafts were used for straight sections, while square shafts were used for arriving shafts. This arrangement optimized the use of available space and ensures efficient jacking operations throughout the project.

4.5 Design calculations of pipe jacking starting shafts

4.5.1 Calculations of pipe jacking starting shafts

(1) Net length calculation of the pipe jacking starting shaft

The net length of the starting shaft for the pipe jacking segment is calculated using the following formula (1) (Shanghai Municipal Engineering Design and Research Institute, 2008):

$$L \geq L_2+L_3+L_4+k \tag{1}$$

Where L_2 = Length of the pipe jacking segment (m), reinforced concrete pipe jacking can be taken as 2.0-3.0m; L_3 = Length of the hydraulic jack (m), generally taken as 2.5 m; L_4 = Minimum length of the pipe left in the shaft (m); k = Thickness of the rear support and jacking iron in accordance with the allowance (m), generally take 1.5 m.

For this specific project, the values are: L2 = 2.0 m, L3 = 2.5 m, L4 = 0.5 m, and k = 1.5 m.

Calculating the net length of the starting shaft: L ≥ 2.0 m + 2.5 m + 0.5 m + 1.5 m = 6.5 m.

(2) Inner net width of the pipe jacking starting shaft

The net width of the starting shaft for the pipe jacking segment is calculated using the following formula (2):

$$B=(1\sim3)D + (2\sim2.4) \tag{2}$$

Where B = Net width of the starting shaft (m); D = Pipe outer diameter (m), which is 1.0 m in this project; 1～3 = Coefficient, which is 1.5 in this project; 2～2.4 = Coefficient, which is 2.2 in this project.

Therefore, the net width of the starting shaft, B = 1.5 × 1.0 m + 2.2 m = 3.7 m.

(3) The depth of the pipe jacking starting shaft

Based on the layout of the sewage pipe jacking, the depth of the shafts should be considered in combination with the depths of the upstream and downstream shafts. In this project, the starting point is the 1# pipe jacking arriving shaft. The sewage pipeline is designed for gravity flow from this starting point. Based on the starting point's invert elevation, the invert elevation of the downstream 1# pipe jacking starting shaft is calculated to be 1925.20 m, with the ground elevation at 1931.70 m. To facilitate the pipe jacking construction operation, a clearance of 0.90 m is reserved at the bottom of the shaft as the construction operation space. Hence, the invert elevation of the 1# pipe jacking starting shaft is 1925.20 - 0.90 = 1924.30 m, resulting in an actual depth of 7.40 m for the 1# pipe jacking starting shaft. Additionally, a 1.50 m height is reserved at the top for the shaft to serve as the inspection chamber's shaft bore height, resulting in the actual depth of the 1# pipe jacking starting shaft being 5.90 m, as shown in Table 1.

Table 1. List of Pipe Jacking Starting shafts

No.	Name	Specification	Material	Remarks
1	1# Pipe Jacking Starting Shaft	L×B×H=6.5×3.7×5.9 m	Reinforced Concrete	L, B, and H represent the net dimensions
2	2# Pipe Jacking Starting Shaft	Φ×H=6.5×10.4 m, Circular	Reinforced Concrete	
3	3# Pipe Jacking Starting Shaft	Φ×H=6.5×12.7 m, Circular	Reinforced Concrete	
4	4# Pipe Jacking Starting Shaft	Φ×H=6.5×12.7 m, Circular	Reinforced Concrete	
5	5# Pipe Jacking Starting Shaft	L×B×H=6.5×3.7×1.9 m	Reinforced Concrete	
6	6# Pipe Jacking Starting Shaft	Φ×H=6.5×2.9 m, Circular	Reinforced Concrete	

4.5.2 Design of Pipe Jacking Starting Shafts

Based on the onsite investigation, a total of six Pipe jacking starting shafts have been designated for this project. The specific layout is illustrated in Figure 2.

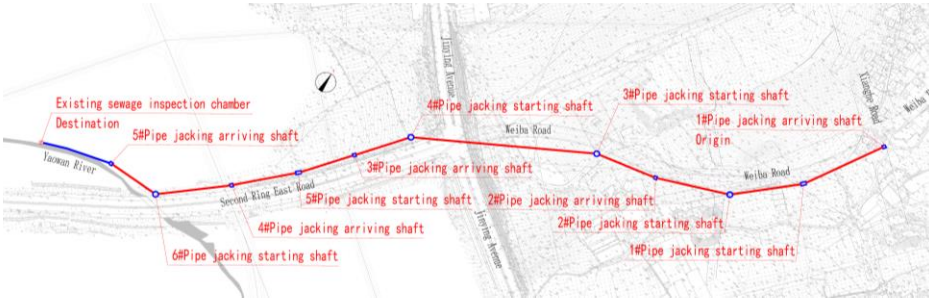

Figure 2. Illustration of Sewer Pipe jacking Plan Layout

The pipe jacking starting shafts are constructed using reinforced concrete structures, with sinking shaft construction performed in excavations at a depth of 1.5 m and a slope ratio of 1:1. Typical designs are shown in Figure 3 and Figure 4.

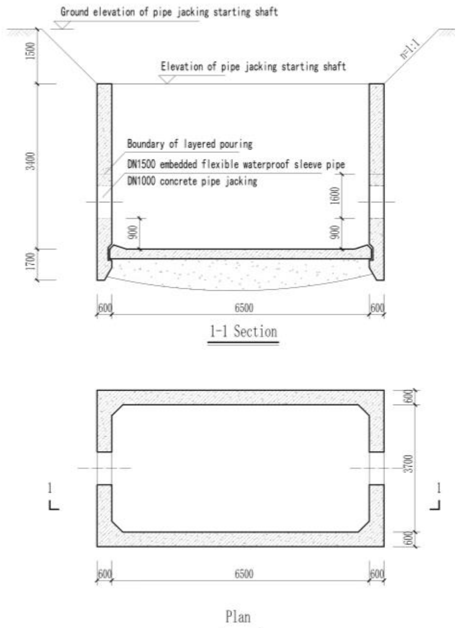

Figure 3. Typical Design of Rectangular Pipe jacking Staring Shaft

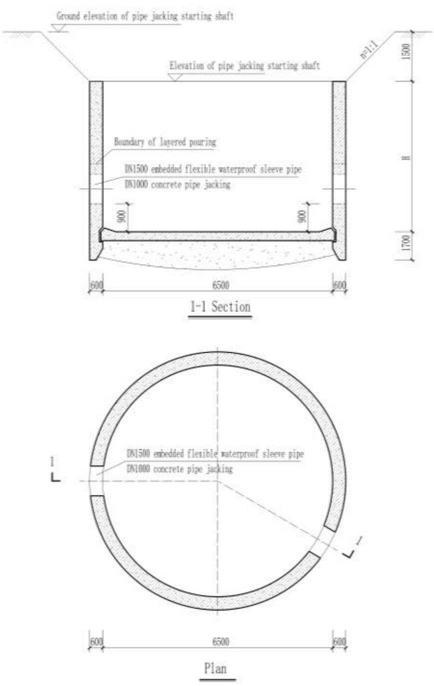

Figure 4. Typical Design of Circular Pipe jacking Starting Shaft

4.6 Design and Calculation of Pipe jacking Arriving Shafts

Based on the previous information, a total of 5 Pipe jacking arriving shafts are set in this project. The planar shape of the Pipe jacking arriving shafts is chosen to be square, with a reinforced concrete structure and constructed through the sinking shaft construction method.

4.6.1 Calculation of pipe jacking arriving shafts

(1) Minimum net width of pipe jacking arriving shafts

The minimum net width of the arriving shafts is calculated using the following formula (3):

$$B = D_1 + 2 \times 1000 \quad (3)$$

Where B = Minimum net width of the arriving shafts (mm); D_1 = Outer diameter of the pipe jacking machine (mm), considering 1200 mm for this project.

The minimum net width of the pipe jacking arriving shafts is B = 1200 + 2 × 1000 mm = 3.20 m. Considering an appropriate margin, the value of B is taken as 3.7 m.

(2) Depth of Pipe jacking Arriving shafts

The depth of the pipe jacking arriving shafts is determined by the ground elevation and the inverted elevation. For instance, the ground elevation at the location of 1# Pipe jacking arriving shaft is 1929.53 m, and its invert elevation is determined by the invert elevation of the incoming pipe. After considering various pipeline intersections, the inverted elevation of the incoming pipe is 1925.53 m. To facilitate the pipe jacking construction operation, a height of 0.90 m is reserved as the operational space below the bottom of the pipe. Therefore, the internal invert elevation of the 1# Pipe jacking arriving shaft is 1925.53 - 0.90 = 1924.63 m, resulting in an actual depth of 4.90 m for the 1# Pipe jacking arriving shaft. Additionally, a height of 1.50 m is reserved at the top for the construction of the inspection chamber, making the actual depth of 1# Pipe jacking arriving shaft 3.40 m.

Similarly, the net internal depth of 2# to 5# Pipe jacking arriving shafts can be calculated, as shown in Table 2.

Table 2. List of Pipe jacking Starting shafts

No.	Name	Specification	Material	Remarks
1	1# Pipe Jacking Arriving Shaft	L×B×H=3.7×3.7×3.4 m	Reinforced Concrete	L, B, and H represent the net dimensions
2	2# Pipe Jacking Arriving Shaft	L×B×H=3.7×3.7×10.2 m	Reinforced Concrete	
3	3# Pipe Jacking Arriving Shaft	L×B×H=3.7×3.7×9.7 m	Reinforced Concrete	
4	4# Pipe Jacking Arriving Shaft	L×B×H=3.7×3.7×3.3 m	Reinforced Concrete	
5	5# Pipe Jacking Arriving Shaft	L×B×H=3.7×3.7×1.9 m	Reinforced Concrete	

(3) Calculation of receiving hole

The calculation for the receiving hole size is as follows (4):

$$D' = D_1 + 2(c + 100) \quad (4)$$

Where D' = Diameter of the receiving hole (mm); D_1 = Diameter of the pipe jacking machine (mm), which is considered as 1200 mm in this project; c = The absolute value of allowable deviation for the pipe (mm), value is taken as 50 mm for this project, considering straight jacking.

Therefore, D’ = 1200 + 2 × (50 + 100) mm = 1500 mm.

And the diameter of the receiving hole is DN1500.

4.6.2 Design of pipe jacking arriving shafts

The pipe jacking arriving shafts are designed as a reinforced concrete structure and constructed as sunk shafts within a pit with a depth of 1.5 m and a slope ratio of 1:1. The typical design is illustrated in Figure 5.

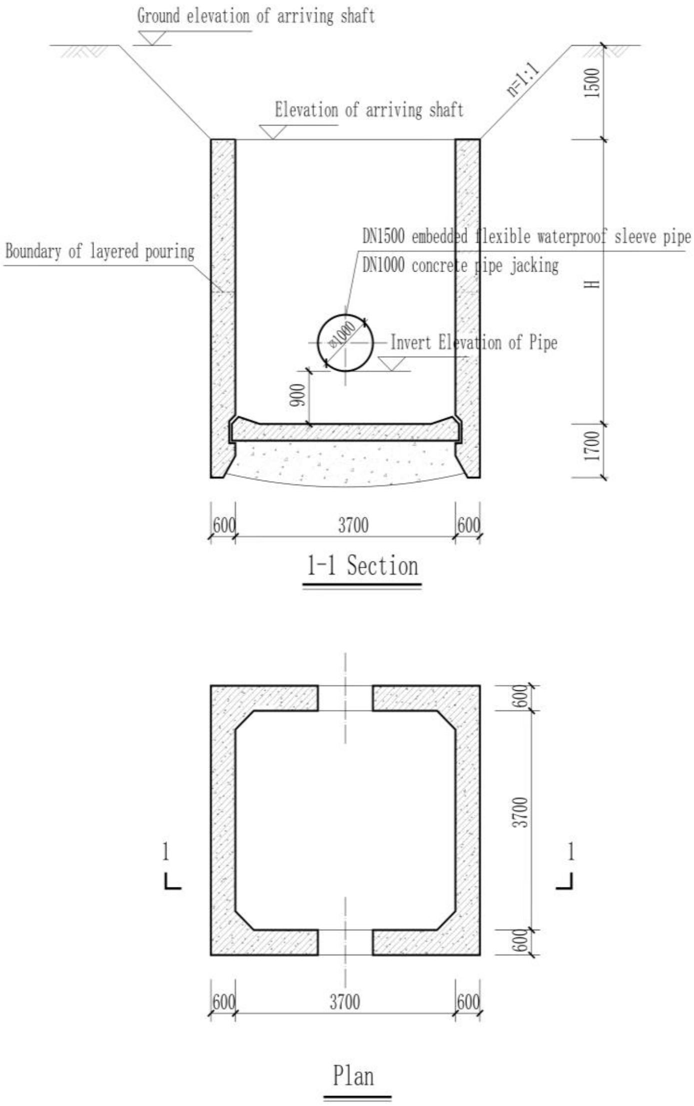

Figure 5. Typical Design of Pipe jacking Arriving Shafts

4.7 Key Points for converting pipe jacking shafts into sewer inspection chambers

Upon the completion of the sewer pipeline jacking construction, both the starting shafts and arriving shafts need to undergo transformation and restoration to ground level, which is crucial to ensure the site and drainage safety of the subsequent construction. The bottom section of the pipe jacking shafts is filled with plain concrete to a height of 0.90 m, while the top section is constructed with reinforced concrete to form a cover slab. Inspection chambers, equipped with ladders, are installed on the cover slab. Both the pipe jacking starting and receiving shafts are converted into sewer inspection chambers, with a chamber height of 1.5 m. The top surface of the pipe jacking starting and arriving shafts are excavated to create a 1:1 slope, and backfilling is carried out in accordance with the relevant pipeline construction standards. Specific details of the transformation are illustrated in Figure 6.

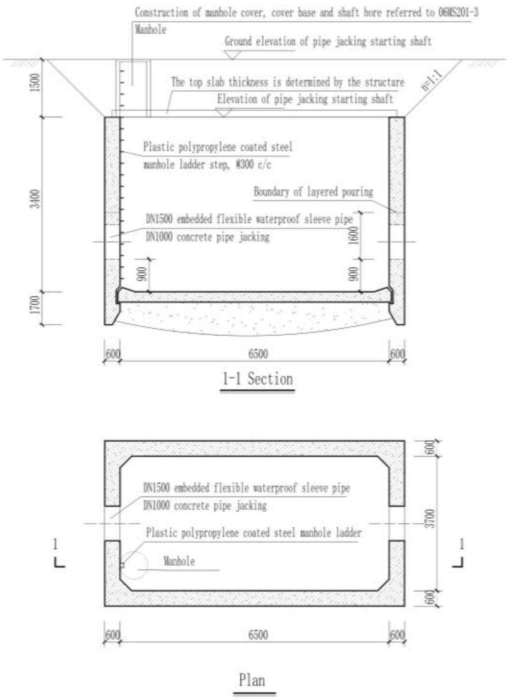

Figure 6. Typical Design of the conversion of pipe jacking starting shafts to sewer inspection chambers

5 Conclusion

The drainage and sewage interception project in Zhaoyang District involves the installation of a DN1000 municipal sewage pipeline with a length of 1541 m. After considering factors such as geological conditions, pipe diameter, buried depth, groundwater level, nearby underground and above-ground structures, and traffic impact, the pipe jacking method was selected through a comprehensive technical and economic analysis. The design includes considerations for pipe diameter, pipe material, pipeline alignment, and the design of pipe jacking starting and receiving shafts in accordance with the practical requirements of the project. The project has successfully undergone completion and acceptance inspection, demonstrating stable operations with all indicators meeting the designated requirements as per the initial design.

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