

Article

Construction Technology and Service Performance of Waterproof Curtain for Foundation Pit in Large-Particle Pebble Gravel Layer of Yangtze River Floodplain

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Abstract: A foundation pit is constructed in the floodplain of Yangtze River, and a deep and thick layer of large-particle pebble gravel exists below the base slab, thus forming a connected supply channel with the adjacent Yangtze River. The large water volume, high water pressure, and strong permeability of this layer bring great risks to the foundation pit construction. In view of the fact that conventional waterproof curtain construction technologies such as the deep mixing column and high-pressure jet grouting column cannot meet the engineering requirements under these kinds of geological and environmental conditions, a new waterproof curtain construction technology that combines the trenching technology of the diaphragm wall with the TRD (Trench cutting Remixing Deep wall) technology is proposed, i.e., the trenching-and-replacing-style TRD technology, as well as the construction process of this technology, is presented. After the waterproof curtain is built using the proposed technology, the strength, integrity, uniformity, and service performance of the waterproof curtain wall are tested and evaluated by the comprehensive methods of coring, borehole television imaging, resistivity CT, and a group well pumping test. The results show that the proposed technology overcomes the adverse effects of underlying large-particle pebble gravel layer, and the waterproof curtain built by it effectively cuts off the hydraulic connection inside and outside the pit. The technical proposal can provide useful references for similar projects.

Keywords: large-particle pebble gravel; foundation pit; waterproof curtain; construction technology; detection technology



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1. Introduction

In recent years, with the rapid development of underground space in China, a large number of foundation pit projects have emerged, and the geological and environmental conditions have become increasingly complex [1–4]. When the stratum where the foundation pit is located is rich in groundwater, it may cause the pit wall leakage, basal heave, surface collapse, etc. [5–7]. It is reported that about 60% of underground engineering accidents are caused by groundwater [8]. Therefore, it is necessary to take some measures to reduce the adverse effects of groundwater. The waterproof curtain is widely used in engineering as an effective waterproof measure [9,10], and its construction quality has a significant impact on foundation pit safety and environmental responses.

At present, the commonly used construction technologies for waterproof curtains include the deep mixing column [11,12], jet grouting column [13,14], sleeve valve pipe grouting [15], freezing method [16], etc. For the above technologies, the construction depth is generally less than 30 m, so it is difficult to cut off the hydraulic connection inside and outside the pit. Moreover, the suitable strata conditions for deep cement mixing column and jet grouting column are clay, silt, and other strata with low strength. In the dense sandy

soil or pebble stratum, there exist some problems such as difficult mixing and spraying, as well as poor construction quality.

Due to the limitations of geological conditions and construction workmanship, the waterproof curtain inevitably has some quality defects, such as leakage, cavities, and cracks [17,18]. Therefore, there is a need to detect the construction quality of the waterproof curtain before excavation. At present, the commonly used nondestructive detection technologies for waterproof curtain defects include thermal [19–23], sonic [24–26], electromagnetic [27–29] methods, etc. However, each detection method has its technical applicability and emphasis. As the waterproof curtain faces complex geological and environmental conditions, if only one detection method is adopted, the detection results may not reflect the real situation objectively, so it is necessary to adopt multiple detection methods for comprehensive evaluation.

In this study, a foundation pit was constructed in the floodplain of Yangtze River, and a deep and thick pebble gravel layer exists below the base slab with high water pressure and strong permeability. In view of the fact that the conventional construction technologies for waterproof curtains such as the deep mixing column and jet grouting column are difficult to meet the engineering requirements, a new waterproof curtain construction technology that combines the trenching technology of the diaphragm wall with the TRD (Trench cutting Remixing Deep wall) technology is proposed, i.e., the trenching-and-replacing-style TRD technology, and the construction process of this new technology is introduced. After the waterproof curtain was built using this technology, the strength, integrity, uniformity, and service performance of waterproof curtain were tested and evaluated by the comprehensive methods of coring, borehole television imaging, resistivity CT, and a group well pumping test. It is expected that the research can provide useful references for similar projects.

2. Site Conditions

2.1. Introduction of Foundation Pit Project

The foundation pit is in Pukou District, Nanjing, and it is an underground 2~3-floor basement with a plane area of 57,298 m² and a perimeter of 1180 m, as shown in Figure 1. The absolute elevation of the underground 3-floor basement slab is −7.40 m, and the excavation depth is 15 m. The absolute elevation of the underground 2-floor basement slab is −2.40 m, and the excavation depth is 10 m. There exist municipal roads, underground pipelines, and factory buildings around the foundation pit, which put forward a high requirement for the control of environmental deformation.

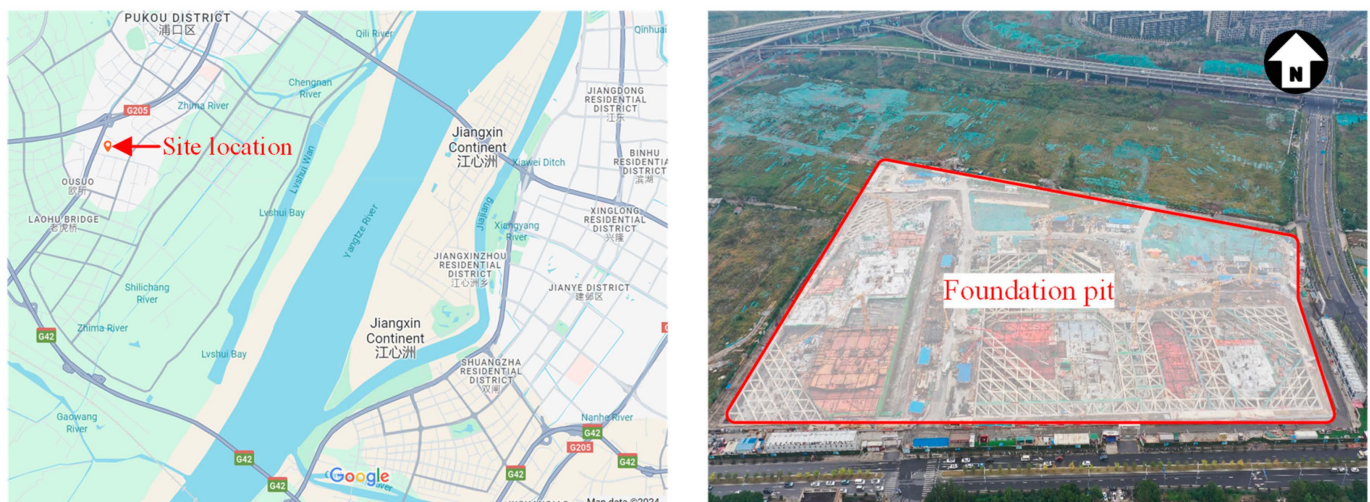


Figure 1. Site location and photo of the foundation pit.

2.2. Engineering Geological Conditions

The construction site of the foundation pit is located at the junction of the Nanjing Yangtze River floodplain and the Laoshan Mountain range. According to the comprehensive analysis of drilling, as well as field and laboratory tests, the strata within the exploration depth have been classified into six layers and twelve sublayers from top to down, which are: ①-1 miscellaneous fill, 1-② plain fill, ② silty clay, ③-1 muddy silty clay mixed with silt, ③-1a silty sand mixed with silt, ③-2 silty clay, ④-1 silty clay, ④-2 silty clay, ⑤-1 pebble gravel, ⑤-2 gravelly sand, ⑥-1 strongly weathered argillaceous siltstone, and ⑥-2 strongly-moderately weathered argillaceous siltstone. Among them, the ⑤-1 layer of pebble gravel has a particle size of 20~100 mm, and individual particles can reach 150~300 mm; the ⑤-2 layer of gravelly sand has a particle size of 10~50 mm, and individual particles can reach more than 80 mm, as shown in Figure 2.



Figure 2. Representative core samples of ⑤-1 and ⑤-2 layers: (a) Core samples of pebble gravel. (b) Core samples of gravelly sand.

Table 1 shows the physical and mechanical parameters of strata in the construction site. It was found that the ①-1 and ①-2 layers have loose structure, low strength, medium–high compressibility, and belong to weakly permeable strata. The ②, ③-1, and ③-2 layers are in a soft–flowing plastic state and have low strength, medium–high compressibility, and belong to slightly–weakly permeable strata. The ④-1 and ④-2 layers are in hard–soft plastic state and have medium compressibility, and they belong to slightly permeable strata. The ⑤-1 and ⑤-2 layers have medium~low compressibility and high permeability. The ⑥-1 and ⑥-2 layers have high strength and slight permeability, which are good bearing and waterproof layers.

Table 1. Physical and mechanical parameters of strata.

Strata	γ (kN/m ³)	ω (%)	e	I_L	E_s (MPa)	c (kPa)	φ (°)	K_0	k_x ($\times 10^{-6}$ cm/s)	k_y ($\times 10^{-6}$ cm/s)
①-1	18.00	—	—	—	—	10.00	12.00	0.50	800.00	600.00
①-2	18.00	26.10	0.78	0.53	4.47	20.00	10.00	0.55	100.00	80.00
②	19.30	28.10	0.81	0.59	5.06	24.50	14.60	0.51	3.31	2.50
③-1	18.10	37.50	1.06	1.54	4.36	14.70	13.40	0.59	25.33	17.92
③-1a	19.20	25.90	0.76	—	9.73	6.80	28.60	0.50	690.20	618.20
③-2	19.00	30.10	0.87	1.01	5.46	18.00	15.30	0.59	12.62	8.88
④-1	19.80	24.30	0.70	0.55	6.41	30.50	15.30	0.50	5.05	3.67
④-2	20.10	22.80	0.67	0.22	7.83	49.70	17.10	0.45	3.83	2.99
⑤-1	20.00	—	—	—	—	5.00	40.00	—	30,000.00	30,000.00
⑤-2	20.00	—	—	—	—	5.00	35.00	—	20,000.00	20,000.00
⑥-1	21.00	—	—	—	—	30.00	25.00	—	80.00	50.00
⑥-2	23.00	—	—	—	—	100.00	30.00	—	10.00	8.00

Note: γ —unit weight; ω —water content; e —void ratio; I_L —liquidity index; E_s —compression modulus; c —cohesion; φ —internal friction angle; K_0 —lateral pressure coefficient; k_x —horizontal permeability coefficient; k_y —vertical permeability coefficient.

2.3. Hydrogeological Conditions

The groundwater in the site includes pore phreatic water, confined water, and bedrock fissure water. Pore phreatic water exists in the ①, ②, ③-1, ③-1a, and ③-2 layers, and the groundwater level is 1.3~2.5 m below the ground surface. It is mainly supplied by the

lateral runoff of atmospheric precipitation, surface water, and irrigation water, and this water is mainly excreted by atmospheric evaporation. It is prone to cause collapse, sand flow, and leakage, and it has a great impact on the construction. Confined water exists in the ⑤-1 and ⑤-2 layers, and the confined water head is 3.8~4.3 m below the ground surface. It is mainly supplied by the lateral runoff of Yangtze River water. The confined water head can probably cause a sudden surge at the bottom of the foundation pit, and this has a great impact on the construction. The bedrock fissure water exists in the joints and cracks of the underlying ⑥-1 and ⑥-2 layers, which is poor in water quantity and permeability and has little impact on the construction.

Figure 3 shows typical geological profiles of the foundation pit. The base slab of the underground 3-floor basement is mainly located on the ③-2 and ④-1 layers, and that of the underground 2-floor basement is mainly located on the ③-1 layer and partially located on the ③-1a and ③-2 layers. The base slab of the underground 3-floor basement is closer to the ⑤-1 layer of pebble gravel and ⑤-2 layer of gravelly sand with a high confined water head.

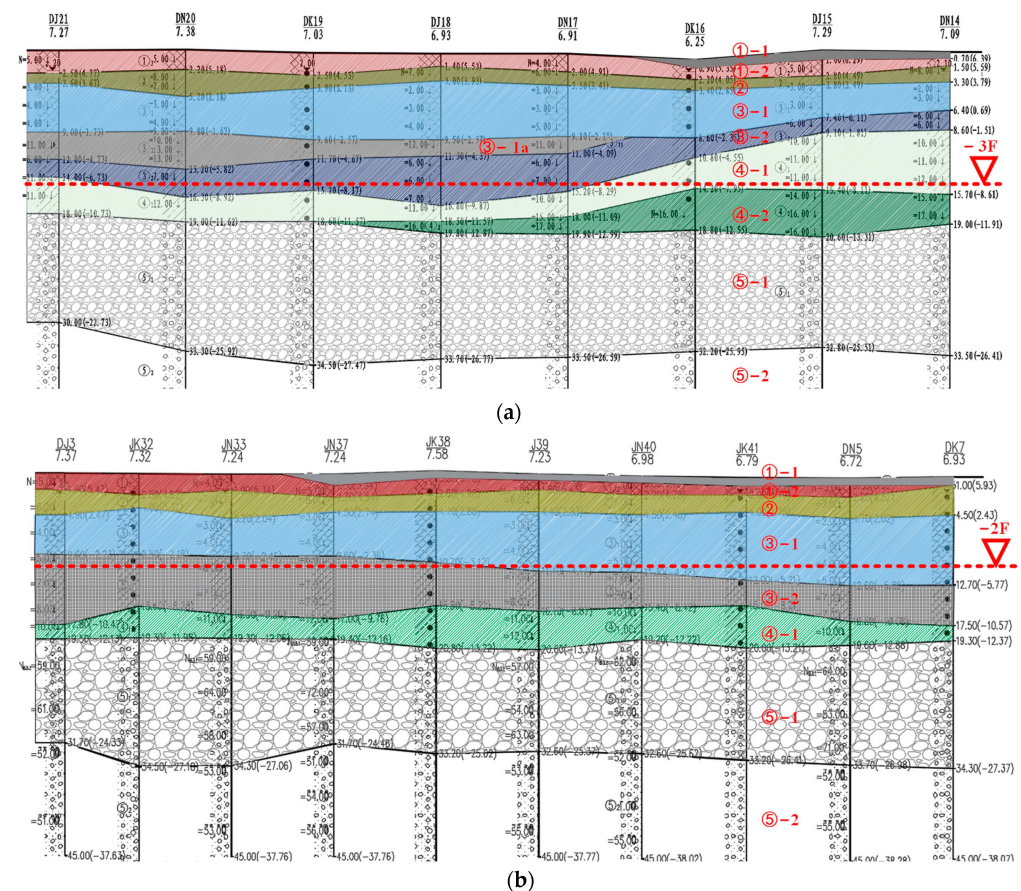


Figure 3. Typical geological profiles of construction site: (a) Geological profile of underground 3-floor basement. (b) Geological profile of underground 2-floor basement.

2.4. Engineering Difficulties

The foundation pit is in the floodplain landform of the Yangtze River, and the engineering geological and hydrogeological conditions are extremely complicated. The shallow and middle layers are soft soil with a high groundwater level and a rich water quantity. Under the base slab of foundation pit, there exist two thick layers of pebble gravel and gravelly sand with large particle sizes and high permeability, which have a strong hydraulic connection with the adjacent Yangtze River and a high confined water head.

To cut off the hydraulic connection inside and outside the pit, the waterproof curtain should reach a depth of 60 m, and its bottom should be inserted into the ⑥ layer of

strongly–moderately weathered argillaceous siltstone at least 1 m. It is difficult to build a waterproof curtain penetrating through the ⑤-1 and ⑤-2 layers of large-particle pebble gravel, and the construction quality is difficult to be guaranteed. The conventional waterproof curtain construction technologies, such as the deep mixing column and high-pressure jet grouting column, struggle to meet the depth and quality requirements.

3. Design and Construction Technology of Waterproof Curtain

3.1. Design of Waterproof Curtain

Because the plane area of the foundation pit is large, and the thick confined aquifers exist under the base slab, double-row cast-in-place piles (A-B-C-D-E-F, C-c-b-a-d-E) were used as the retaining structure to divide the original superlarge foundation pit into two areas for zoned excavation. TRD (Trench cutting Remixing Deep wall) technology was used to build a waterproof curtain between two rows of piles to cut off the underlying confined aquifers, and tube well dewatering and open drainage of the water were used in the pit to low the groundwater level, as shown in Figure 4.

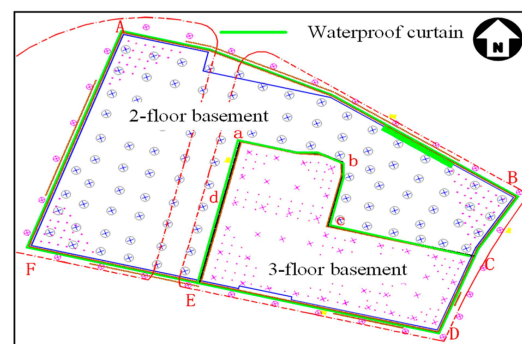


Figure 4. Diagram of waterproof curtain of foundation pit.

TRD technology, also known as the Trench cutting Remixing Deep wall method, is a new construction technology for waterproof curtains that has been widely used in recent years [30–32]. It uses a chain saw cutter to cut the soil horizontally and then injects cement slurry to mix with the in situ soil to form a continuous cement–soil wall with equal thickness, as shown in Figure 5. The waterproof curtain wall built using TRD technology can reach a depth of 60 m, the verticality is not more than 1/250, and the wall has good homogeneity and reliable waterproof performance. It has a good adaptability in soft clay, dense sand with an SPT blow count of 50–60, gravel with a diameter less than 100 mm, and soft rock with an unconfined compressive strength not more than 5 MPa [33,34].

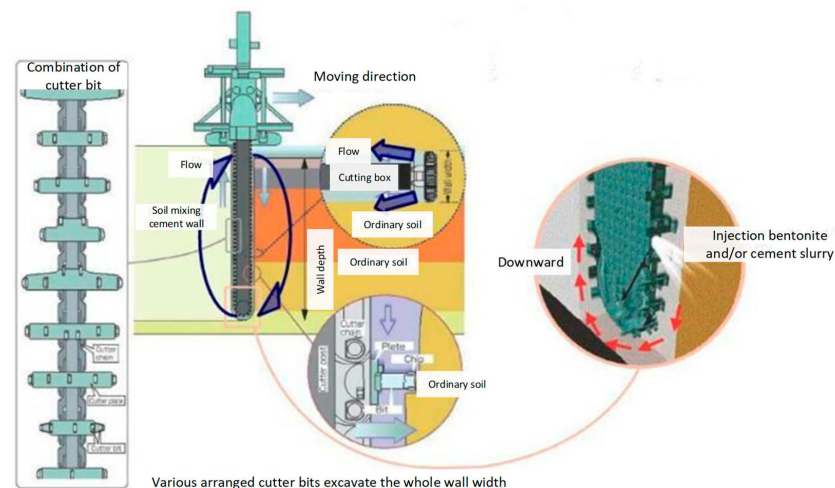


Figure 5. Schematic of the TRD technology.

In this project, due to the existence of pebble gravel with a particle size of 150~300 mm and the depth of the waterproof curtain wall being 40~63 m, the conventional TRD construction technology is prone to cause problems such as serious wear of the cutter, lower construction efficiency, and lower wall quality when the machine penetrates the pebble gravel and gravelly sand layers. Therefore, the traditional TRD technology needs to be improved to better adapt to the engineering conditions.

3.2. Trenching-and-Replacing-Style TRD Technology for Waterproof Curtain

In view of the problems in the traditional TRD technology under these complicated engineering geological and hydrogeological conditions, the trenching-and-replacing-style TRD technology, which combines the trenching technology of the diaphragm wall with the traditional TRD technology, has been proposed.

This technology is generally implemented in three steps: (1) Excavating the trench using a trenching machine for the diaphragm wall; (2) replacing the large-particle pebble gravel and backfilling the homogeneous cohesive soil in the trench; and (3) cutting and mixing the cement–soil to build a continuous and homogeneous waterproof curtain wall using TRD technology. Figure 6 shows the schematic diagram of the construction process. The technical points of each step are described as follows:

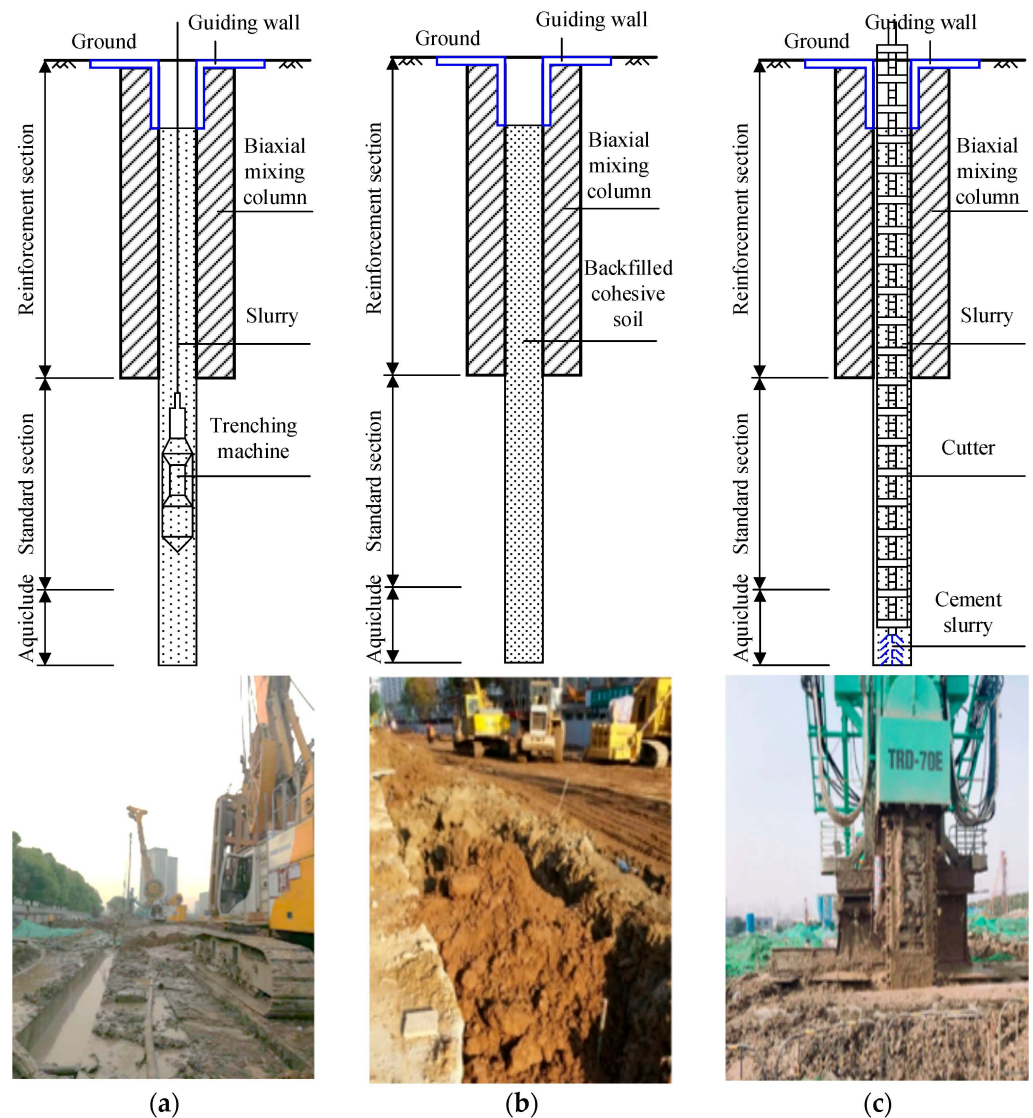


Figure 6. Construction process of trenching-and-replacing-style TRD technology: (a) Step 1. (b) Step 2. (c) Step 3.

(1) Step 1: excavating the trench

To ensure that the bottom of the waterproof curtain wall enters the ⑥-2 layer of strongly–moderately weathered argillaceous siltstone, the high-power trenching machine of BAUER BG80S was adopted to excavate the trench. The width and depth of the trench came out to 0.8 m and 63 m, respectively. In the process of trenching, the trench wall is prone to collapse, so the following measures were taken:

1. Before trenching, the trench wall was reinforced using biaxial mixing columns, and the guide wall was constructed, as shown in Figure 6a. The reinforcement depth came out to 11 m, thus reaching the bottom of the ③-1 layer of silty clay. The cement used is ordinary Portland cement with strength grade of 42.5, the cement content is 15%, and the water–cement ratio is 0.5.
2. High-quality bentonite was used, CMC tackifier was added to prepare mud to protect the trench wall, and barite powder was used to appropriately increase the mud proportion, thus making it in the range of 1.15~1.18. The mud level in the trench was kept at least 0.5~1.0 m higher than the groundwater level.
3. In the process of trenching, the grab bucket of the trenching machine enters and exits the trench slowly and steadily. Especially in the pebble gravel layer, the trenching speed keeps slowly. The interval trenching mode was used to control the trenching width.
4. Stacking heavy objects and the walking of large machinery around the trench were avoided to prevent instability and collapse induced by overloading on the surrounding ground surface.

(2) Step 2: replacing large-particle gravel

After the trenching depth of each trench section reached the design depth confirmed by geological exploration, we backfilled the silty clay in time to replace the large-particle gravel, and the backfilling amount was about 2/3 of the excavated soil volume, as shown in Figure 6b. The next trench section could be built only after the previous trench section was backfilled.

(3) Step 3: building the waterproof curtain wall

After the large-particle pebble gravel in the trench was replaced by backfilling the silty clay, TRD technology was used to build the waterproof curtain wall according to the following steps, as shown in Figure 7:

1. Primary cutting of soil: After the cutter box was placed to the expected depth, the bentonite fluid was injected, and the cutter box moved horizontally to cut a section of backfilled soil, as shown in Figure 7a.
2. Retreat cutting of soil: After cutting a section of backfilled soil was completed, the cutter box retreated horizontally to the starting point to cut the soil again, and it overlapped the wall formed in the previous section by 30~50 cm, as shown in Figure 7b.
3. Mixing to form wall: After the cutter box was retreated to the starting point, the cement curing liquid was injected, and the cutter box moved forward horizontally to mix with the soil to form a section of cement–soil wall with equal thickness, as shown in Figure 7c.

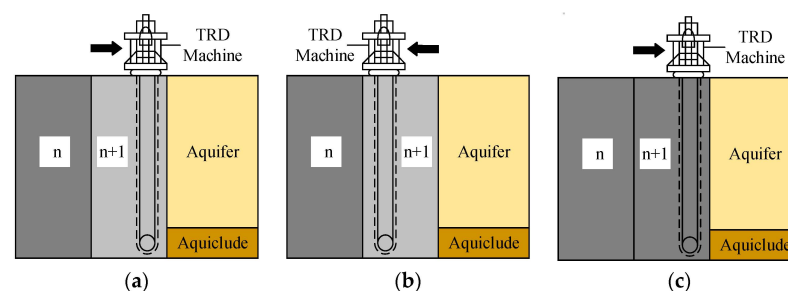


Figure 7. Construction process of waterproof curtain using TRD technology: (a) Primary cutting of soil. (b) Retreat cutting of soil. (c) Mixing to form wall.

4. Quality Detection of Waterproof Curtain

4.1. Coring and Lab Tests

To evaluate the quality of the waterproof curtain constructed by the trenching-and-replacing-style TRD technology, the core samples were obtained by drilling for lab tests. Considering that a conventional single-tube drilling tool cannot obtain the complete core samples from the pebble gravel layer, and the borehole below a certain depth may deviate from the wall with low verticality, it was optimized to a single-driving double-tube drilling tool for coring, as shown in Figure 8a. The single-driving double-tube drilling tool has an inner tube and an outer tube, and the drill pipe only drives the outer tube to rotate, but the inner tube does not rotate, which can avoid the mechanical breakage of the core sample caused by rotation-induced friction vibration, thus improving the coring quality.

A total of 15 boreholes were drilled along the edge of the foundation pit for coring. Figure 8b shows the representative core samples obtained from the borehole with a depth of 45 m in the underground 3-floor basement area. It was found that after using the single-driving double-tube drilling tool, continuous core samples were obtained along the depth of waterproof curtain, and the coring quality in the pebble gravel layer and gravelly sand layer was significantly improved.



Figure 8. Core samples obtained by drilling for lab tests: (a) Drill pipe for coring. (b) Core samples of waterproof curtain.

After coring, the strength and particle compositions of the core samples were obtained through lab tests, as listed in Table 2. It was found that the unconfined compressive strength of the core samples in the silty clay was greater than 1.0 MPa, and that in the gravel was even greater than 4.0 MPa, which met the requirements that the wall strength should be not less than 1.0 MPa. The particle size of the core samples in the gravel was obviously smaller than that before the waterproof curtain was built, and the large-particle gravel was removed. This implies that the adopted trenching-and-replacing-style TRD technology effectively overcomes the problems of difficult construction and poor quality of the waterproof curtain in deep and large-particle pebble gravel layers.

Table 2. Unconfined compressive strength and particle composition of core samples.

Depth H (m)	Strata	Number of Core Samples N	Strength M (MPa)	Particle Size
0~6	Fill/clay	96	0.8	Fine particle
6~12	Silty clay	96	1.1	Fine particle
12~18	Silty clay	96	1.2	Fine particle
18~24	Pebble	42	2.1	2~5 cm
24~32	Pebble	27	1.8	2~5 cm
32~40	Gravel	35	1.5	1~3 cm
40~46	Gravel	38	3.3	1~3 cm
46~55	Gravel/mudstone	42	4.2	2~5 cm

4.2. Borehole Television Imaging

After core drilling was completed, the borehole television imaging detection method was adopted to convert the 360° borehole image into a 2D plane image and fed back to the ground terminal in real time. The main components of borehole television imaging equipment include a high-definition camera, signal collector, depth measuring device, transmission cable, image analyzer, etc., as shown in Figure 9a.

Figure 9b shows the borehole image of the waterproof curtain wall. It was found that the integrity of the waterproof curtain is relatively good, with more gravel particles in the broken core position and less gravel in the intact core position. The results of the borehole television imaging provide a direct and strong proof for the detection results of core drilling.

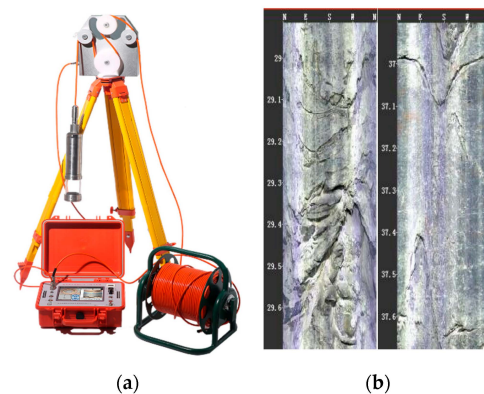


Figure 9. Borehole television imaging equipment and results: (a) Borehole television imaging equipment. (b) Images in the borehole.

4.3. Resistivity CT

The waterproof curtain is formed by mixing and solidifying the in situ soil with cement, and its resistivity should be higher than that of surrounding undisturbed soil. When there are quality problems in the waterproof curtain, such as low cement content, thin curtain thickness, defects or discontinuities in the curtain, the resistivity in these potential weak areas will be reduced. Resistivity CT uses this principle to detect the quality of waterproof curtain.

Figure 10 shows the equipment of resistivity CT and the arrangement of detection holes. Four boreholes are symmetrically arranged on the two sides of the waterproof curtain in the form of plane rectangle, wherein the short side is 2 m, the long side is 20 m, and the depth of the boreholes is 2 m deeper than that of the waterproof curtain to ensure that the transmitting and receiving paths of electric signals can cover the wall. Based on the data obtained by the equipment, the resistivity distribution between the four boreholes is obtained through 3D inversion technology, and then the resistivity distribution at the position of the waterproof curtain is obtained.

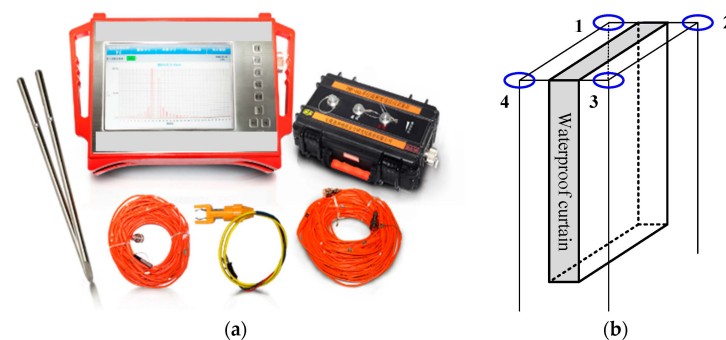


Figure 10. Equipment and detection holes arrangement of resistivity CT: (a) Resistivity CT equipment. (b) Arrangement of detection holes.

In reference to the resistivity of the qualified section detected by coring and borehole television imaging, the 2-level resistivity thresholds of $10 \Omega \cdot \text{m}$ and $20 \Omega \cdot \text{m}$ were adopted to evaluate the quality of the waterproof curtain. The specific evaluation criteria are as follows: if the resistivity distribution is uniform and $\rho > 20 \Omega \cdot \text{m}$, the quality of the waterproof curtain is very good; if the resistivity distribution is relatively uniform and $10 \Omega \cdot \text{m} < \rho < 20 \Omega \cdot \text{m}$ for most of regions, the quality of the waterproof curtain is good; if the resistivity distribution is relatively uniform and $\rho < 10 \Omega \cdot \text{m}$ for a local region, there may be discontinuous defects in the region with low resistivity; and if $\rho < 10 \Omega \cdot \text{m}$ for most of regions, the quality of the waterproof curtain is bad.

After the waterproof curtain was built, a total of 25 sections of the waterproof curtain were detected using resistivity CT along the edge of the foundation pit. Figure 11 shows two representative detection results of the waterproof curtain corresponding to the underground 2-floor and 3-floor basement areas. It was found that the resistivity in the detection area was larger than $10 \Omega \cdot \text{m}$ and even exceeded $50 \Omega \cdot \text{m}$. In the vertical direction, the resistivity distribution along the depth of the waterproof curtain was uniform without a low resistivity region, and in the horizontal direction, the joint area showed a high resistivity, thus inferring that this may be due to the overlap of two pieces of the waterproof curtain during construction. The detection results show that the quality of the waterproof curtain constructed by the trenching-and-replacing-style TRD technology is good, thus overcoming the adverse effects of the large-particle gravel strata.

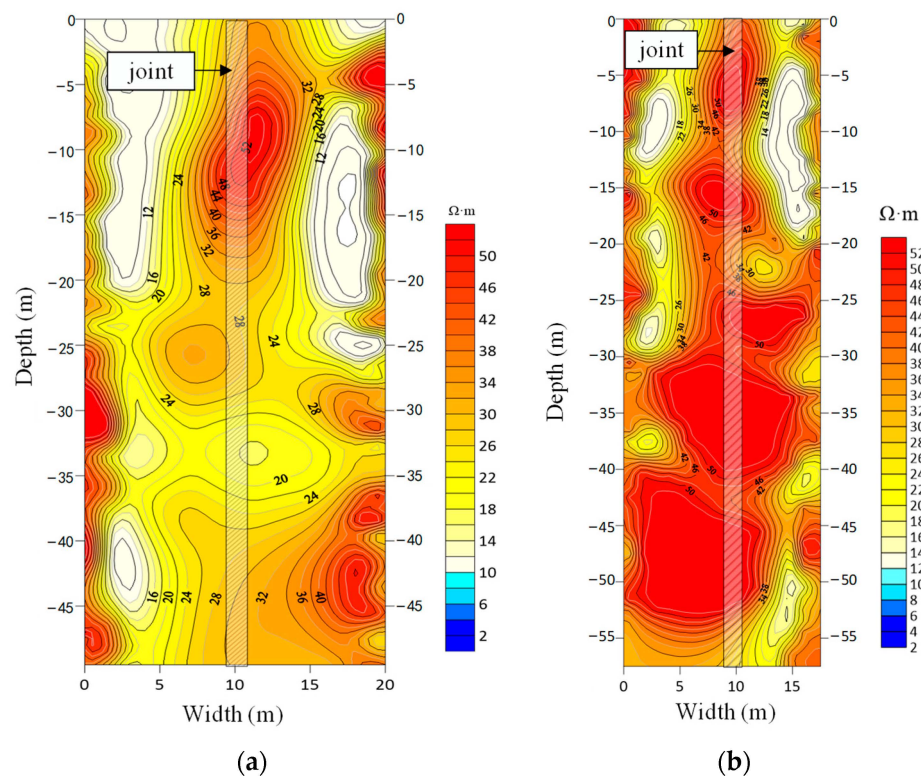


Figure 11. Detection results of waterproof curtain by resistivity CT: (a) Waterproof curtain in 2-floor basement. (b) Waterproof curtain in 3-floor basement.

4.4. Group Well Pumping Test

Using the above detection technologies, the quality of the waterproof curtain in a local position or region was evaluated. To evaluate the overall service performance of the waterproof curtain, a group well pumping test was carried out in the southeast corner of the foundation pit corresponding to the area of the underground 3-floor basement. As shown in Figure 12, seven pumping wells (JS 1~JS 7) with wellhead elevations of 5 m in the pit and eight observation wells (GC 1~GC 8) with wellhead elevations of 7 m outside the

pit were set. During the pumping process, the water level change in the observation well was observed synchronously.

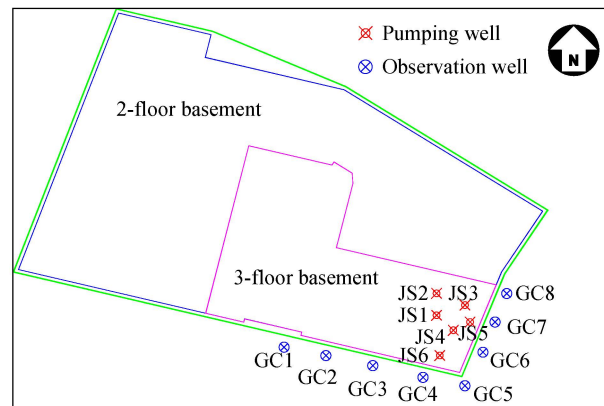


Figure 12. Plan layout of pumping well and observation well.

Figure 13 shows the changes of the water level in the pumping wells and observation wells. It was found that the elevation of the water level in the pumping well fluctuated and decreased with the time, and the elevation of the water level in the observation wells was relatively stable, thus keeping at about 4.0 m. This shows that the waterproof curtain effectively cuts off the hydraulic connection inside and outside the pit and has obvious waterproof performance. During construction, it can be ensured that the groundwater level in the pit is lowered below the base slab without affecting the water level outside the pit.

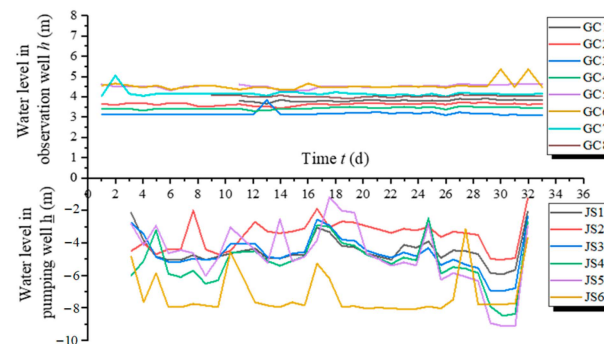


Figure 13. Water level in the dewatering well and observation well.

5. Conclusions

In view of the problems that the underground gravel stratum of a foundation pit on the Yangtze River floodplain is deeply buried and has high water pressure and strong permeability, a new trenching-and-replacing-style TRD technology was proposed, and the construction process was introduced. After the waterproof curtain was built using this technology, the strength, integrity, uniformity, and waterproof properties of the waterproof curtain wall were tested and evaluated using comprehensive methods of coring, borehole television imaging, resistivity CT, and group well pumping tests. The following conclusions have been obtained:

(1) The deep and thick large-particle gravel stratum below the foundation pit determines that the depth of the waterproof curtain should be 40~63 m to cut off the hydraulic connection inside and outside the pit. The traditional deep mixing column and high-pressure jet grouting column cannot meet the depth and quality requirements, and the traditional TRD technology has the problem of serious cutter wear.

(2) The construction process of the proposed trenching-and-replacing-style TRD technology mainly includes three steps: excavating the trench, replacing large-particle pebble gravel, and building the waterproof curtain wall.

(3) The unconfined compressive strength of the waterproof curtain built by the proposed trenching-and-replacing-style TRD technology was more than 1.0 MPa, the particle size of gravel in the core sample was obviously reduced, and the uniformity, integrity, and joint lap quality of the wall were good.

(4) The waterproof curtain effectively cuts off the hydraulic connection inside and outside the pit, and it can ensure that the ground water in the pit is lowered below the base slab without affecting the water level outside the pit.

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