

Research Article

Study on the Factors Affecting the Quality of Trench Cutting Remixing Deep Wall in Qingdao Area

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As a new type of waterproof curtain, several station construction of Qingdao Metro Line 1 successfully used the trench cutting remixing deep wall (TRD). It is difficult to find the factors that affect the wall quality because the method is in situ underground excavating and mixing. This paper has obtained the main factors affecting the TRD quality in Qingdao by studying construction experience and carrying out tests. Geological conditions are fundamental factors. Among them, the parameters of medium-coarse sand layer, the groundwater table, and the humus content are the main factors. The design parameters are the key to high-quality TRD. In the design parameters, the depth inserting into the bedrock, the cement soil ratio, and the mixing time are important factors. And this paper proposes the methods of improving the wall quality, which can provide a theoretical guarantee for the follow-up application of the TRD in the Qingdao area.

1. Introduction

The length of the line of Qingdao Metro Line 1 (Figure 1) is about 60 km, and a total of 39 stations are underground stations. Qingdao is a coastal city with a shallow and abundant groundwater table of about 1-5 m. But the station depth is 20-30 m, and most of the station is below the groundwater table. The groundwater seriously affects the quality and efficiency of the pit construction. The 39 stations must implement water-stop works before pit construction [1-4].

As a new type of waterproof curtain, TRD (Figure 2) has the advantages of deep construction depth, wide adaptability to the stratum, reliability, and safety. Several open excavation stations have applied this method, such as the Miaotou Road Station, Nanling Road Station, Zunyi Road Station, Zhengyang Road Station, Chunyang Road Station, and Shengliqiao Station. The water-stop projects are successful in the above various construction.

This method was invented in 1993 by Kobe Steel, Japan. It was introduced to China in 2005 and then applied in many

projects. Many coastal and riverside cities used this method, such as Shanghai, Tianjin, Hangzhou, Nanchang, and Changsha [5]. The principle is to use a saw chain cutter to excavate and mix the in situ soil with the postinjected cement slurry to form the waterproof curtain. The specific operation (Figure 3) is as follows: first, insert the chain cutter into the foundation and dig to the design depth of the wall; secondly, inject the cement slurry and mix with the in situ soil, then continue to horizontally excavate, mix, and advance to build a high-quality TRD [6]. The TRD machine excavates and mixes this layer with other layers, which not only destroys the continuity of the aquifer but also increases the strength of the solidification mud due to the addition of aggregate.

During the construction process, there is no other way to check the wall quality except for the engineering experience at present. The detection methods of TRD are coring, water injection test, sound wave, geological radar, etc. and only implemented after cement soil solidification [7]. The detection methods are useful for discovering large leakage areas but not for small leakage points. If the leakage occurs during

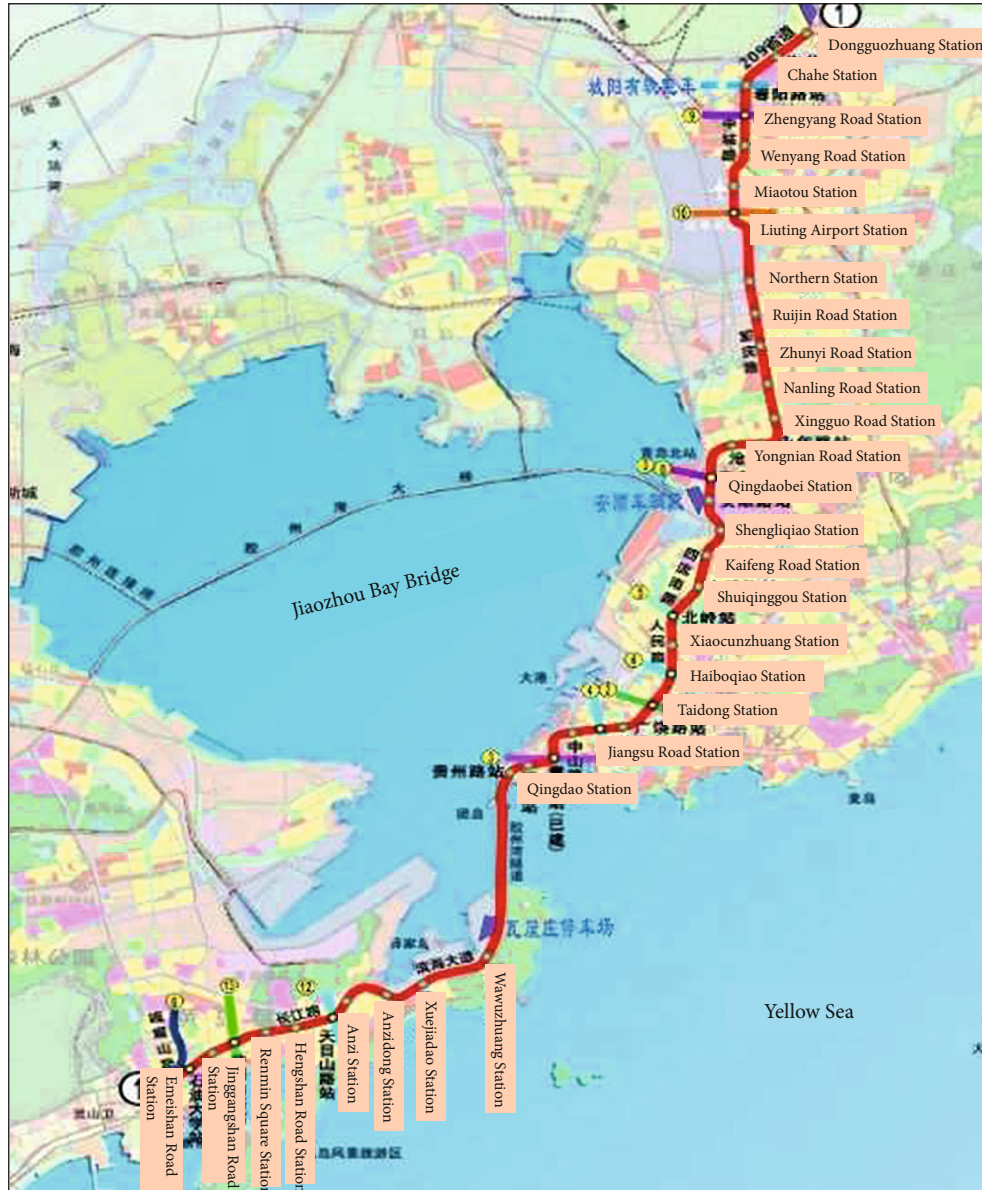


FIGURE 1: Qingdao Metro Line 1 floor plan.

the excavation, it may seriously affect the construction safety. Because medium-coarse sand is an aquifer, even small leaks of water may cause piping. The remediation process is complex, and the effect is difficult to guarantee.

The predecessors have carried out more research on the factors affecting the cement soil mixing methods of different methods. In the deep mixing method, several factors which can be roughly divided into four categories influence the magnitude of the strength increase of treated soil by lime or cement [8]. Rong [9] studied the construction parameters of cement deep mixing piles (CDM) and pointed out key reasons to ensure construction quality. The influence of four construction parameters is analyzed such as slurry conveying capacity, drilling and hoisting speed, agitation shaft rotation speed, and remixing times on pile quality. Zhang [10] analyzed the design and construction techniques for soil mixing wall (SMW) with a large diameter. Special attention was

given to good applicability, low construction cost, and short construction period. The above researches have studied various types of cement soil mixing method but not the influencing factors of TRD.

This paper has obtained the main factors affecting the TRD quality by studying experience and carrying out tests in Qingdao, which prevent the quality problem in the future application. Geological factors are the root cause, and the design parameters are the key to high-quality TRD. In response to the influencing factors, this paper proposes countermeasures of improving the TRD quality. It can provide a direction for the future application of the TRD in the Qingdao area.

2. Geological Factors

The stratum of Qingdao Metro Line 1 construction area is Quaternary strata (Table 1) and bedrock. Quaternary strata



FIGURE 2: TRD machine in working.

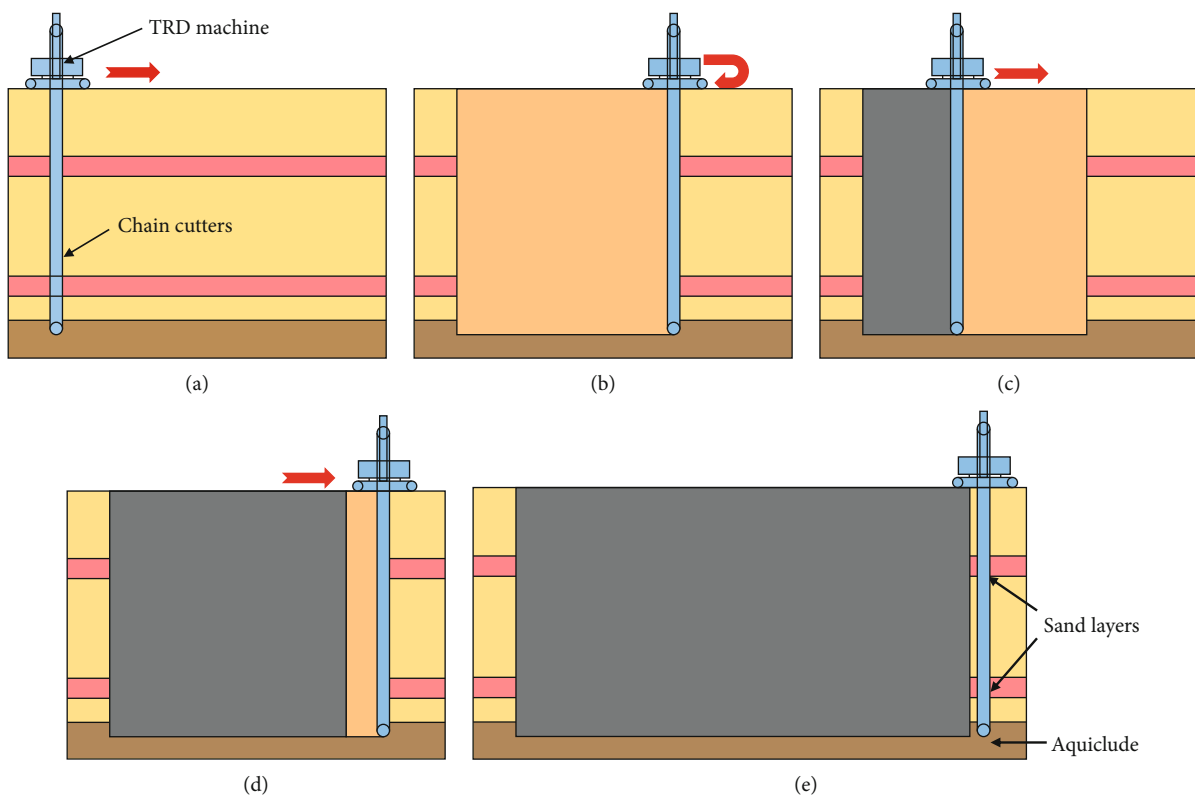


FIGURE 3: Schematic diagram showing the steps of the TRD method. (a) Insert the saw chain cutters. (b) Cut and mix the soil mass and inject bentonite slurry. (c) Inject cement slurry and mix. (d) Go to the next section. (e) Pull out the cutters after having completed.

thickness is 0.30 to 29.60 m, and the average value is 13.20 m. Bedrock is strongly weathered and rich in joint fissures. The medium-coarse sand layer is the aquifer from the results of the geological survey [1].

In the Qingdao area, TRD passes through the entire Quaternary system, so many geological factors are influencing the construction. Based on laboratory tests and theoretic

cal analysis [11–13], the parameters of medium-coarse sand layer, groundwater table, and humus content are the main geological factors affecting the quality of the wall.

2.1. Parameters of Medium-Coarse Sand Layer. The medium-coarse sand layer is the aquifer and the treated layer in the Qingdao area. And its parameters determine the water-

TABLE 1: Thickness of each layer in the Quaternary system of Qingdao area.

No	Description	Thickness (m)	Aquifer
1	Backfill	0-2	No
2	Medium-coarse sand	0-1.2	Yes
3	Silty clay	2-5	No
4	Medium-coarse sand containing humus	0-1.6	Yes
5	Medium-coarse sand	0.5-1.8	Yes
6	Silty clay containing humus	1.2-2.5	No
7	Silty clay~silt	1.1-1.9	No
8	Medium-coarse sand containing humus	0-1.7	Yes
9	Medium-coarse sand	0.5-2.3	Yes
10	Silty clay~clay	0.8-2.1	No
11	Coarse sand	0-1.5	Yes
12	Silty clay~clay	0-5	No

stopping effect, in which the thickness, depth, relative position of the groundwater table, and grain composition are the main influencing factors.

2.1.1. Thickness. When the construction depth of the TRD is determined, the thicker the sand layer, the thinner the clay layer, the lower the clay ratio and the viscosity of the mixed mud, which is beneficial to excavation. However, this is not conducive to mixing and the formation of mud cake (Figure 4) [14]. Because the mud wraps the sand to move under the cutter action and the strength of the mud cake is not enough to support the excessively thick noncohesive sand layer to collapse into the trench, if the sand layer collapses, it will affect the trench stability. Cement and clay together improve TRD impermeability, and lower clay content will reduce it.

2.1.2. Depth. The groundwater level divides the sand layer of the treated area into two parts, above and below the water table. The table is very shallow (1-5 m) in Qingdao, so the sand layer above the groundwater level is close to the surface. When there is a sand layer above the groundwater table, the TRD machine is unstable in construction (Figure 5). Because of the low strength of the sand layer does not support the TRD machine weight (100 t) [15] and the permeability is too high to form the mud cake, the cutting fluid and cement slurry may outflow during construction. When outflow occurs, the slurry table is lowered in the trench, further affecting the stability of the tank wall. The unstable layer under the groundwater is the critical treatment area which TRD isolates.

2.1.3. Particle Composition. In addition to the above two parameters, before the cement soil solidifies, the larger particles will settle and form the bottom sedimentary zone, which will also affect the treatment at the deep part of TRD.

According to the solid-liquid two-phase flow theory [16], the formula for the velocity of the particle moving in

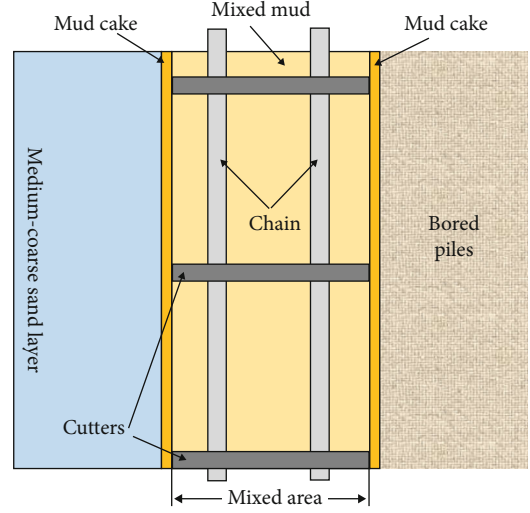


FIGURE 4: Schematic diagram of mixing and mud cake formation.

Bingham fluid is as follows: (1) In the process of excavating and mixing, the mixed mud is a Bingham fluid, and the assumption is satisfied. Therefore, the formula is also applicable to the cement soil.

$$u_s = \frac{d}{\eta_{\infty}} \left[0.0702gd(\rho_s - \rho_f) - \tau_0 \right], \quad (1)$$

where u_s is the velocity of the particle (m/s), d is the ultimate suspended particle size (m), τ_0 is the ultimate shear strength of the mixed mud (N/m^2), ρ_s is the sand particle density (kg/m^3), ρ_f is the mixed mud density (kg/m^3), and g is the gravitational acceleration (m/s^2).

$u_s = 0$, and the particles are in suspension, so the ultimate suspended particle size is

$$d_s = \frac{\tau_0}{0.702g(\rho_s - \rho_f)}. \quad (2)$$

The particles settle when the particle is larger than the particle size.

$$t = \frac{H}{u_s}, \quad (3)$$

where t is settling time (s) and H is the depth of the particle from the bottom of the wall (m).

When the sedimentation phenomenon occurs, the calculated amount of sedimentation particles is obtained based on the particle-size distribution curve (Figure 6) [17]. The field tests determine the settlement correction coefficient, the thickness of the sediment layer, and the influence of the sediment layer on the wall performance [18].

2.2. Underground Water Table. The shallower groundwater table results in more leakage if any leaks happen. The water pressure difference is high between both sides of the wall after the station excavated.

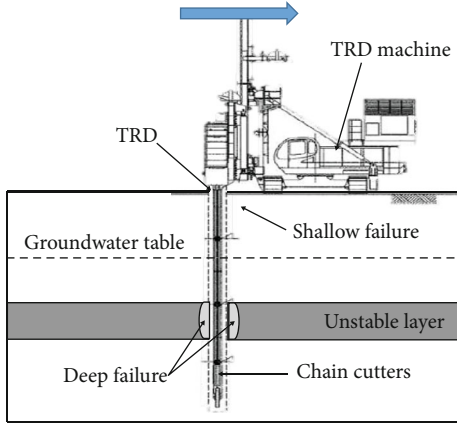


FIGURE 5: Profile of the sand layer failure in TRD construction.

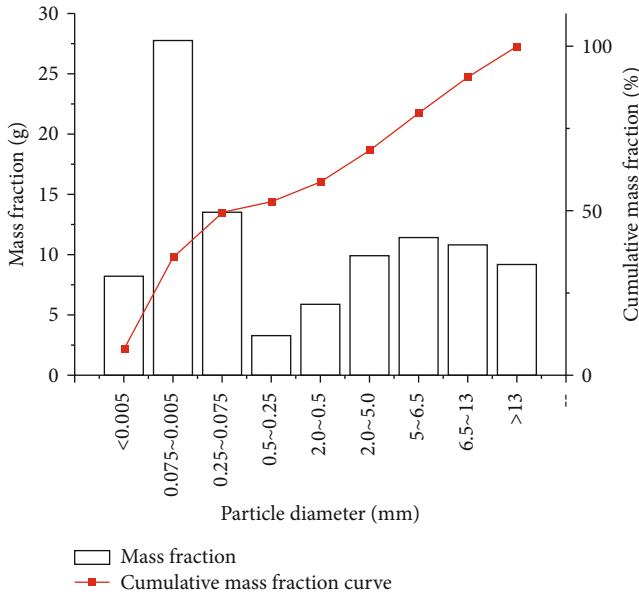


FIGURE 6: Particle-size distribution curve of medium-coarse sand layer.

It is assumed that the bedrock of the pit is impermeable and the sides of the TRD are vertical (Figure 7). According to the formula of the nonpressure seepage on the impervious foundation under the vertical boundary conditions [19]

$$q = \frac{k(H^2 - h^2)}{2L}, \quad (4)$$

where q is the seepage flow (m^3/s), k is the permeability coefficient of TRD (m/s), H is the groundwater level outside the TRD (m), h is the groundwater level inside the TRD (m), and L is TRD thickness (m).

The formula shows that the flow is independent of the leakage point height and inversely proportional to the wall thickness. Moreover, the water pressure difference is higher on both sides of the wall, and the flow is more.

When the other parameters are unchanged, the higher the groundwater table, the higher the moisture content of

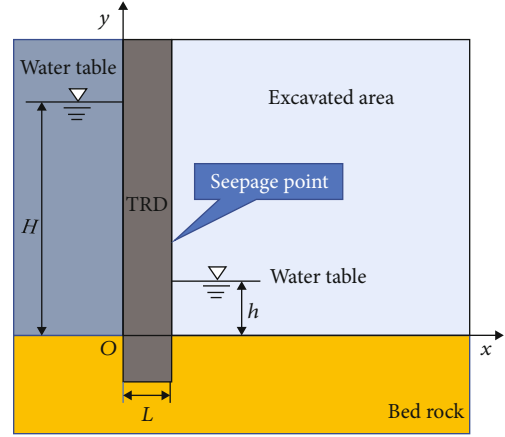
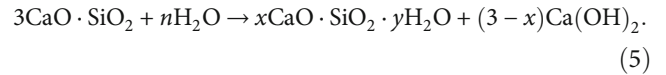


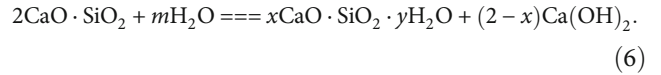
FIGURE 7: Nonpressure seepage on impervious foundation under vertical boundary conditions.

cement soil after mixing. Through laboratory tests, the higher the moisture content of the cement soil, the worse the compressive strength and impermeability of the sample (Figures 8 and 9).

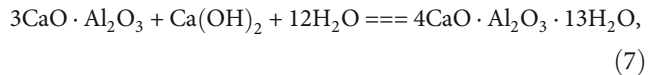
2.3. Humus Content. Tricalcium silicate hydration formula is as follows:



Dicalcium silicate hydration formula is as follows:



Tricalcium chlorate hydration formula is as follows:



where x is CaO/SiO_2 .

In the quaternary system of Qingdao, some areas contain more humus (Table 1) which will seriously affect the strength and impermeability of TRD. The main components of humus are fulvic acid and humic acid, and their effects on cement soil strength are not the same. In the fulvic acid, water, and cement system, fulvic acid firstly as the aqueous solution contacts with cement, and then cement hydration reaction occurs. However, the adsorption layer formed by the adsorption of fulvic acid and cement minerals delays the progress of cement hydration reaction. At the same time, the fulvic acid could decompose the aluminium-containing minerals, dissolve the crystals of hydrated calcium aluminate, destroy the structure, and reduce the strength of the cement soil. The decomposition of fulvic acid affects the early strength of cement soil and has an inhibitory effect on later strength growth [20].

The humic acid's strong affinity for calcium reflects its effect on the strength of cement soil, which can form calcium

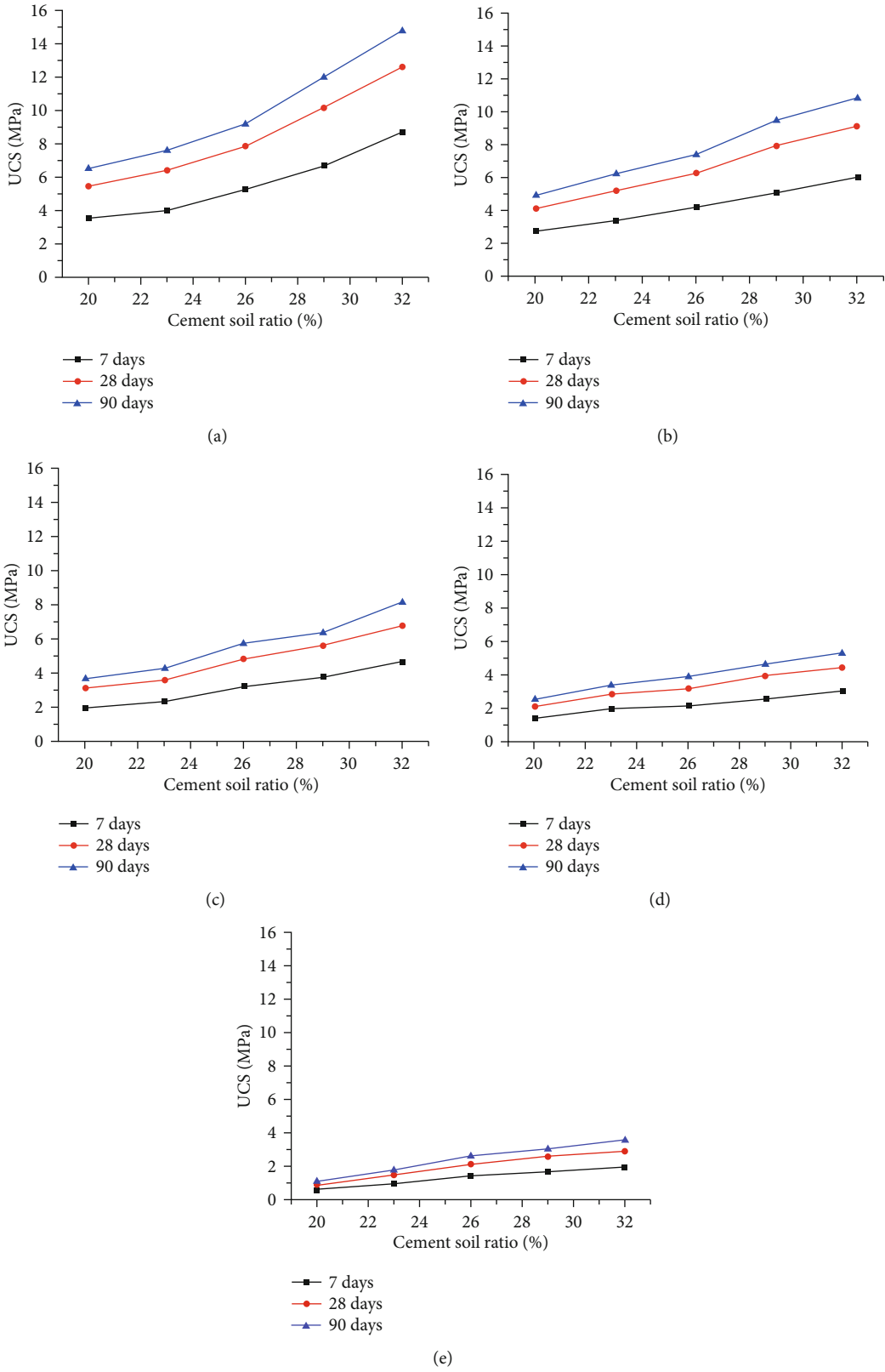


FIGURE 8: Curve of unconfined compressive strength with cement soil ratio. (a) Moisture content 28%. (b) Moisture content 33%. (c) Moisture content 38.5%. (d) Moisture content 43%. (e) Moisture content 48%.

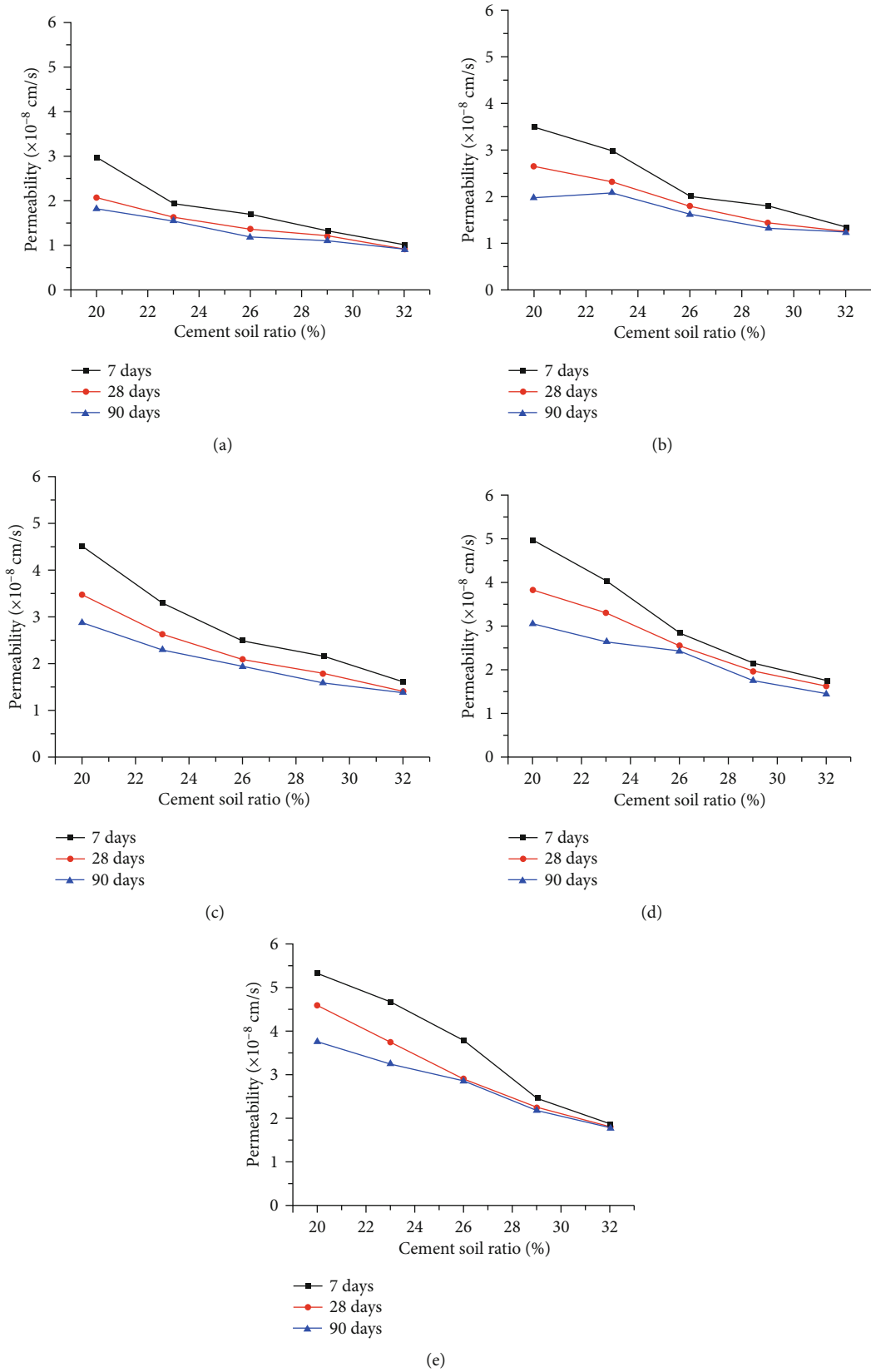


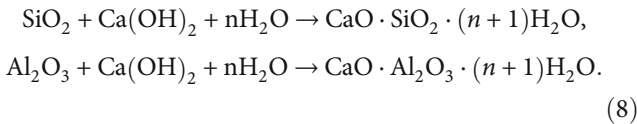
FIGURE 9: Curve of permeability with cement soil ratio. (a) Moisture content 28%. (b) Moisture content 33%. (c) Moisture content 38%. (d) Moisture content 43%. (e) Moisture content 48%.

TABLE 2: TRD main design parameters.

Divisions	Description	Standards
Cutting fluid	Specific gravity of unconsolidated mud	1.6 ± 0.1
	TF value of unconsolidated mud	200 ± 20 mm
Cement slurry	Material	Bentonite
	Injection rate deviation	$\leq 10\%$
	Cement soil ratio	20%
	Water cement ratio	1.2~1.4
	Material	P.042.5 Portland cement
	Grouting pressure	2 MPa
	Fluidity	150 mm~280 mm
Machine parameters	Machine type	LSJ60
	Horizontal excavation speed	< 0.625 m/h
	Vertical mixing speed	> 60 m/min
QC	28 days unconfined compressive strength	> 0.8 MPa
	28 days permeability	$< 1 \times 10^{-7}$ cm/s
	Vertical deviation	$< 1/250$
	Positioning deviation	± 25 mm
	Wall thickness deviation	± 30 mm
	Wall depth deviation	± 30 mm

humate precipitate. The precipitates are neutral and difficult to dissolve. The hydration of Portland cement produces calcium hydroxide, calcium silicate hydrate, calcium hydrated aluminate, etc., and humic acid combines with calcium to precipitate and destroy the cement soil structure. Like fulvic acid, the humic acid can also affect the growth of cement soil strength, especially in the later strength growth [8].

Pozzolanic reaction is as follows:



The volcanic ash reaction is that a large amount of $\text{Ca}(\text{OH})_2$ in the solution is produced after cement hydration, forms a strongly alkaline environment, and reacts with SiO_2 and Al_2O_3 of the soil to generate calcium silicate and calcium aluminate. Then, a gelled structure and a fibrous crystal network structure are gradually formed, which bond the dispersed soil particles together to increase the strength of the cement soil. The fulvic acid and humic acid in the humus neutralize $\text{Ca}(\text{OH})_2$, hindering the pozzolanic reaction and affecting the strength of the cement soil.

3. Design Parameters

The design parameters (Table 2) used in the TRD method are based on Excavation Engineering Manual [21], Specification for Construction of Diaphragm Wall [22], Technical Specification for Soil Mixed Wall [23], Technical Specification for Trench Cutting Remixing Deep Wall [24], and other regula-

tions [25–27] and are determined with the geological conditions in Qingdao.

As shown in the figure, the station (Figure 10) using the TRD method is located above the bedrock and has a depth of about 20 m. The initial supporting system (Figure 10) is bored piles with a diameter of 1000 mm, and the centre distance is 1400 mm. There is a distance of 400 mm between the drilled piles, so it is necessary to construct a waterproof curtain. The 850 mm-thick TRD is close to the bored piles as the waterproof curtain (Figure 11). Depth is 1 m inserted into the bedrock, which prevents the bottom of the pit from leakage because the groundwater may pass through the bedrock fissure.

The core requirement of the TRD method is the impermeability and strength, wherein the impermeability should be less than 1×10^{-7} cm/s, and the uniaxial compressive strength should be greater than 0.8 MPa. When any of the above conditions are not met, the TRD method is considered invalid.

Theoretical and experimental research on the key factors affecting the quality of the wall in the design parameters was carried out [8, 28, 29]. The cement soil ratio directly affects the strength and impermeability of the wall. The mixing time affects the uniformity of the mixing. The depth of the wall into the bedrock affects the stability and the impermeability of the wall.

3.1. Cement Soil Ratio. The cement soil ratio is the cement volume to the undisturbed soil volume:

$$\alpha = \frac{V_c}{V_s} \times 100\%, \quad (9)$$

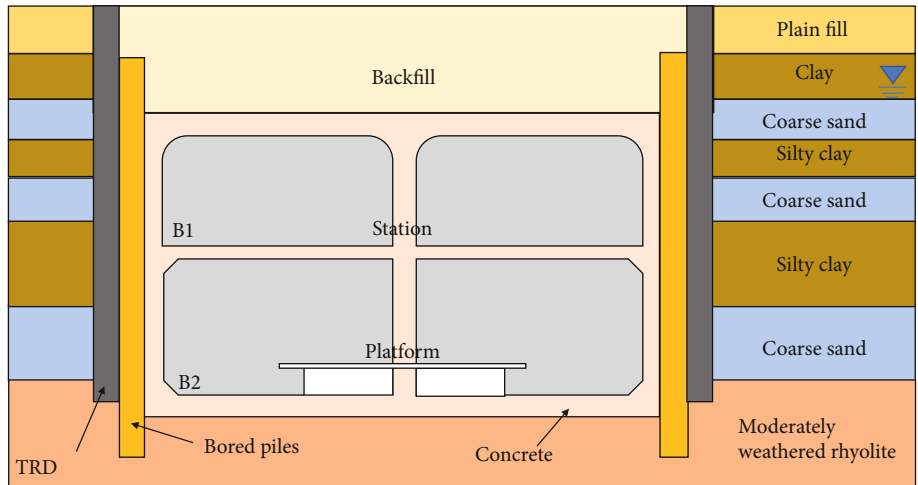


FIGURE 10: Double-storey station profile.

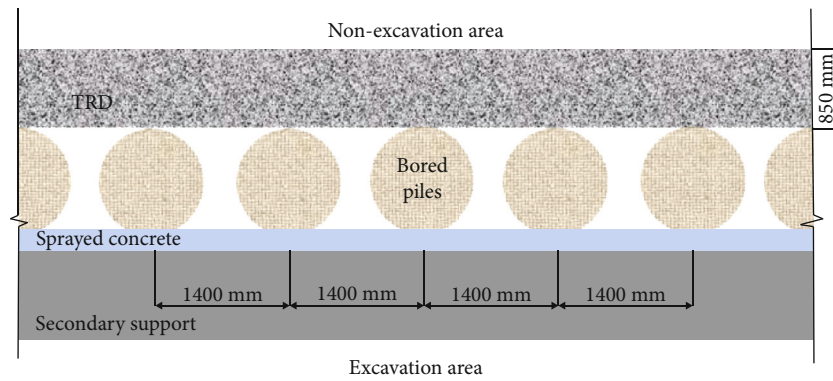


FIGURE 11: TRD position in the support system.



FIGURE 12: TRD model test device [6].

where α is cement soil ratio, V_c is the volume of cement, and V_s is the volume of soil.

In the TRD construction, the cement soil ratio in different areas is different. It is necessary to carry out tests whether mixed cement soil under different mixing ratios could meet the strength and impermeability requirements. Every layer in the construction area constitutes the test

soil, and the proportion is the thickness ratio of average to the total. The cement is P.O42.5 Portland cement. 20% is the minimum cement soil ratio in TRD construction of China. Therefore, the cement soil ratio of tests is from 20% to 32%.

The strength of cement soil increases with the cement soil ratio and curing time and continues to grow after 28 days as

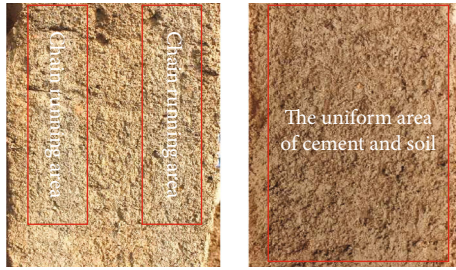


FIGURE 13: Distribution of cement with different mixing time.

shown in Figure 8. The moisture content affects the strength of the cement soil, and the lower the moisture content, the faster the cemented soil strength increases. Taking the 28 days curing period cement soil as an example (Figure 8(a)), when the moisture content is 28%, the strength increases by about 1.79 MPa with each increase 3% of cement soil ratio. However, the strength increases by about 0.5 MPa when the moisture content increases to 48%.

As shown in Figure 9, the higher the cement soil ratio, the lower the permeability coefficient, and the permeability coefficient increases with the curing time and continues to decrease after 28 days curing time. The moisture content affects the permeability coefficient of cement soil. The higher the moisture content, the larger the permeability coefficient, and the more obvious the effect of increasing the cement content on improving the impermeability of cement soil. Taking the 28-day curing time as an example, when the moisture content is 28% and 48%, the permeability, respectively, reduces by 55% and 60% with the cement content increasing from 20% to 32%.

Through the tests, 20% of cement soil ratio meets the strength and impermeability requirements of the TRD in Qingdao. However, the above tests are carried out under mixing uniform. During construction, the machine mixing parameters determine it.

3.2. Mixing Time. The mixing time is the sum of the in situ soil mixing time (Figure 3(b)) and the injected cement slurry mixing time (Figure 3(c)). The mixing factors mainly include vertical mixing speed, horizontal cutting speed, cutting fluid ratio, cutter box parameters, and mixing time [30, 31]. Machine performance determines the first four parameters, which give control criteria in the design. The field tests and experiences decide the mixing time, which becomes an uncertain factor. And other mixing factors influence the mixing time. Therefore, the TRD model test device (Figure 12) is developed to carry out the mixing time tests.

Based on the second similarity theorem, the mixing processes with a depth of 1 m is carried out. Through the comparison of model and field tests, the TRD model test device can simulate TRD mixing process [6].

As shown in Figure 13, the chain running area collects more cement slurry if the mixing time is insufficient. Because the continuity of the chain is conducive to the diffusion of the cement slurry, it is necessary to reasonably control the mixing time before and after injecting cement slurry.

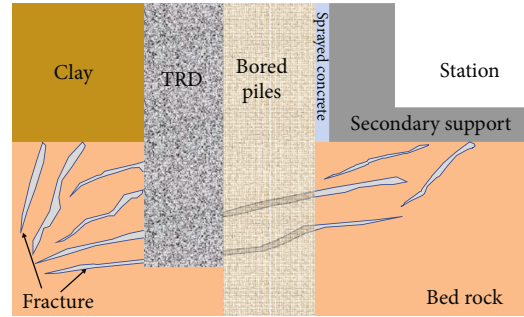


FIGURE 14: Longitudinal schematic diagram of the wall into the bedrock.

3.3. Depth into the Bedrock. The Qingdao area is the typical upper-soft and lower-hard stratum structure. The bedrock is moderately or strongly weathered rocks and rich in joint fissures. The station base is above the bedrock, so it is prone to microcrack leakage. Based on some completed projects, there is no leakage if the depth into the rock meets the design requirements.

As shown in Figure 14, after the bedrock excavated, the cracks are cut off and exposed. The mixed mud and cement slurry are filling into some cracks under a static pressure, which could increase the impermeability of the bedrock around the wall. The insertion depth should adjust with the bedrock fluctuation. The insufficient depth may cause leakage at the TRD bottom. On the contrary, inserted bedrock is too deep, which reduces construction efficiency. Therefore, how to ensure the depth into bedrock has become the technical management focus.

Human factors, especially construction experiences, greatly influence the construction process. This paper only studies the design parameters of the TRD, which does not consider the influence of human factors.

4. Countermeasures

The following countermeasures were proposed for the above affecting factors to ensure the TRD quality in the Qingdao area.

- (1) In the TRD construction area, the geological conditions should be clear. An appropriate amount of carboxy methyl cellulose (CMC) can be added to increase the viscosity of the mixed slurry if the medium-coarse sand layer is thick, or the groundwater table is shallow, which can improve the trench stability and prevent the particle sedimentation
- (2) Lime can neutralize excess acid in the soil when the humus content is relatively high. The decrease of acidity can enhance the strength and impermeability of the cement soil
- (3) 1 m depth into the rock could meet the design requirements. During the construction process, the parameters can judge this depth, such as the cutting depth, the vertical mixing speed, the horizontal

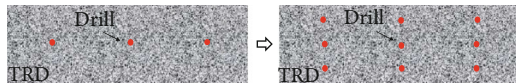


FIGURE 15: The coring position in TRD.

cutting speed, and the rock samples taken out during the construction process

- (4) The strength and impermeability of TRD must meet the design requirements, and the cement soil ratio should not be less than 20%
- (5) Except for the longitudinal direction of the wall, two coring positions (Figure 15) should be increased in the horizontal direction of the wall: front and rear of the wall during TRD field tests to check the mixing uniformity. Samples are reasonably stored and used to conduct mechanical tests
- (6) When leakage occurs during excavation, it should be treated promptly by backfilling, grouting, and so on. The grouting treatment is prepared for each leakage according to its characteristics. And the excavation should be started after the leakages are well controlled
- (7) It is necessary to organize TRD workers to learn and communicate with each other, which is beneficial to improve the technical level of workers and reduce the human factors affecting the TRD quality.

5. Conclusions

Through theoretical analysis and experimental research, the key factors affecting the TRD quality are geological factors and design parameters, and the following conclusions are as follows:

- (1) The medium-coarse sand layer is both an aquifer and a water-guiding layer, and therefore, it is the target layer for treatment. The thickness affects the trench stability, the sand particle content affects the wall impermeability and mixing efficiency, and the settlement of larger particles could form a sediment layer at the bottom of the wall, which may affect the strength of the impermeability of the bottom end of the wall
- (2) The groundwater affects the moisture content of the cement soil. The higher the groundwater table, the more the moisture content of the mixed mud and the worse the permeability and strength of the wall after having completed. If leakage occurs during the excavation, the water pressure difference is larger on both sides of the wall, and the larger the water output, the higher the remediation difficulty
- (3) The humus in the formation is not conducive to the hydration reaction and volcanic ash reaction of the cement soil, which weakens the joint effect between

the soil particles and affects the impermeability and strength of the wall

- (4) The cement soil ratio is one key to affect TRD quality. The higher the amount of cement, the higher the quality of the wall. However, to save costs, the ratio is 20% to meet the quality requirements in Qingdao
- (5) 20% of the cement soil ratio is obtained in the lab. Therefore, to ensure cement soil uniformly mixing and efficient construction, the mixing time should be reasonably determined
- (6) The depth inserting into the bedrock affects the bottom impermeability of the wall. The mixed mud and cement slurry are filling into some cracks under a static pressure, which could increase the impermeability of the bedrock around the wall. It improves the bottom impermeability. The 1 m depth into the bedrock meets the impermeability requirements of the Qingdao area.

At the same time, this paper gives the countermeasures for the above-mentioned influencing factors and provides a theoretical basis for the better application of TRD in Qingdao. It also has important guidance and reference significance for improving quality and safety factor and reducing the construction cost of TRD.

Data Availability

The data used to support the findings of this study are included within the article. And other researchers can use the data in my article for research on TRD.

Conflicts of Interest

There is no conflict of interest regarding the publication of this paper.

Acknowledgments

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