Journal of Materials, Processing and Design (2025)
Clausius Scientific Press, Canada
DOI: 10.23977/jmpd.2025.090105
ISSN 2516-0923 Vol. 9 Num. 1

Study on sexual improvement of red clay in Chongqing

Wang Dalei, Qi Yunpeng

Key Laboratory of Urban and Engineering Safety and Disaster Reduction, Ministry of Education, Beijing University of Technology, Beijing, 100124, China

Keywords: Red clay; permeability coefficient; unlimited strength; drainage rate; curing soil

Abstract: In order to effectively use the solid waste red clay in Chongqing to carry out the basic erosion protection of the local cross-river bridge, the curing agent and cement are used to improve the performance of Chongqing red clay, the influence of curing agent and water-solid ratio on the permeability coefficient, unlimited compressive strength and drainage rate of curing soil is mainly studied. The test results show that the increase of curing agent can significantly improve the impermeability through the mechanism of forming three-dimensional network structure to block the pore channel; the increase of water-fixed ratio will significantly reduce the impermeable performance, and the mechanism is that free water weakens the particle bonding and forms the seepage channel. In terms of mechanical properties, the curing agent has an optimal value (0.3%); the rise of water-solid ratio will weaken the bonding between particles and reduce the compaction of cured soil, resulting in the reduction of unlimited compressive strength. In terms of bleeding performance, the bleeding rate was zero when the amount of curing agent was 0.2%, and the water-solid ratio had no significant effect on the bleeding rate.

1. Introduction

According to statistics, among the 1,716 cases of bridge damage around the world, the massive damage is caused by the erosion of the bridge pier foundation, accounting for 47.49% in the United States, 58.17% in China, and the annual economic loss caused by the United States is as high as 30 million US dollars [1-6]. As a typical mountainous city with many mountains and many rivers, the Yangtze River, Jialing River and other water systems have fast velocity and high sediment content, which leads to frequent accidents of erosion and damage of bridge foundation, highlighting the obvious shortcomings of traditional erosion protection technology.

The current bridge pier erosion protection technology is mainly divided into active protection and passive protection. The active protection method realizes anti-erosion by reducing the flow rate, which mainly includes front row sacrificial pile [7], guard ring protection [8] and bridge pier opening protection [9], etc., but there are widespread defects of contact interface coupling failure, poor adaptability of multi-directional flow field and high maintenance cost. Passive protection method focuses on improving the riverbed erosion resistance ability, its method mainly includes riprap [10] protection method, expand foundation protection [11], concrete film bag protection [12], four foot concrete protection method [13], deepwater construction positioning difficulties, however, mass concrete shrinkage strain, hydration heat aggregation and contact surface stiffness mutation. Fundamentally, the traditional protection methods mostly rely on the macroscopic engineering experience, but the microscopic mechanism of the multiphase interface of soil-water-material is ignored.

Ready-mixed liquid curing soil is an emerging technology in recent years. It takes in situ soil (utilization rate> 85%), low-mixed gelelling materials and special curing agent as raw materials to break through the limitations of traditional protective measures through micro coordination mechanism. Its core advantages are that the elastic modulus matches the riverbed matrix to avoid the interface mutation; eliminating the risk of bulk concrete hydration; [14]; and inhibiting particle loss [15] by enhancing the shear strength of the soil itself. Many scholars at home and abroad have conducted research on the use of solidified soil to protect the foundation of bridge piers.

Du Shuo [16] studied the anti-scour performance of solidified soil and the scour protection effect of solidified soil on offshore wind power foundation. It was found that the protection effect mainly depends on the protection range. Wang et al. [17] studied the significant effect of soil particle grading, while the compaction and density of soil had little effect on the erosion resistance of soil. And [18] and Yuan Jianzhong [19] studied the anti-erosion protection effect of silt solidified soil on offshore wind power foundation. The silt solidified soil can be closely fitted, completely covered and have good protection effect. Ding Jian et al. [20] studied the influence law of different moisture content and the mixing amount of different curing agents on the performance of silt solidified soil, and proposed the method of in-situ silt solidification. Zhou Maoqiang et al [21] compared riprap protection and solidified soil protection, and found that the performance of solidified soil protection is better than that of riprap protection, and believed that solidified soil protection is an alternative method of traditional riprap protection. Li Tengfei et al [22] used ANSYS finite element software to simulate the protection capacity of silt solidified soil on offshore wind power pile foundation, and concluded that solidified soil can improve the horizontal resistance of pile foundation, reduce the deformation, bending moment and stress of pile body, and improve the cohesion of soft soil foundation and reduce the sand bearing capacity of water flow. Ouyang et al. [23] used sinks to wash the pile foundation of cement solidified soil, and obtained the feasibility of this protection method. Shen Xiaolei et al. [24] concluded that solidified soil can significantly improve the horizontal bearing capacity of pile foundation.

Although the above studies have proved that solidified soil has a good effect in erosion protection, the study on the permeability, mechanical properties and bleeding properties of solidified soil is lacking. In this study, based on the red clay, cement as cementing material, laboratory curing agent, the influence of different curing content and different water-solid ratio on curing soil permeability coefficient, unlimited compressive strength and drainage ratio, designed to make a theoretical basis for the design of curing soil mix ratio.

2. Overview of the trial

2.1 Test materials

The soil material used in this test is red clay in Jiangjin District, Chongqing. The particle size distribution curve of soil is shown in Figure 1, and the basic physical and mechanical properties of clay are shown in Table 1. The cement is ordinary Portland cement with a strength grade of 42.5. The curing agent adopts the laboratory homemade curing agent.

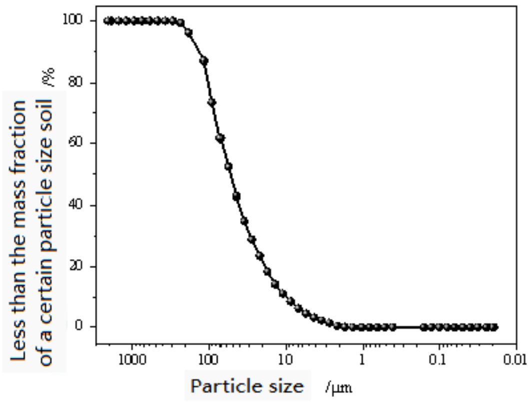

Figure 1 Grade matching curve of red clay particles

Table 1. Main components list of red clay

The type of soil	natural moisture content /%	liquid limit /%	plastic limit /%	plasticity index	Density/ $g \cdot cm^{-3}$
red clay	29.5	34	19.5	14.5	1.73

2.2 Sample protocol

In this experiment, the influence of the change of curing agent and the change of water-solid ratio on the permeability coefficient, compressive strength and drainage ratio of solidified soil were studied. The test scheme is shown in Table 2.

Table 2 Sample ratio design

Sample number	Addition of curing agent	Cement admixture	water-solid ratio
0-0.50	0	10%	0.50
0.1-0.50	0.1%	10%	0.50
0.2-0.50	0.2%	10%	0.50
0.3-0.50	0.3%	10%	0.50
0.4-0.50	0.4%	10%	0.50
0.3-0.60	0.3%	10%	0.60
0.3-0.55	0.3%	10%	0.55
0.3-0.45	0.3%	10%	0.45
0.3-0.40	0.3%	10%	0.40

The sample preparation process is as follows: ① Mix the soil, cement and curing agent well in proportion; ② add quantitative water for wet mixing, stir for 5min to stir the curing soil well to get the curing soil required for the test.

In this test, the proportion of water is the quality of water and cement, cement and soil quality, and the proportion of curing agent is the quality of curing agent and soil. In the test, the water-solid ratio was 0.4 to 0.6, and the amount of curing agent was 0 to 0.4%.

3. Results and discussion

3.1 Permeability analysis

The influence of curing agent dosage on the permeability coefficient is shown in Figure 2. With the increase of curing agent dosage, the permeability coefficient of curing soil is constantly decreasing. It shows that with the increase of curing agent, the permeability permeability of curing soil is gradually better. At 25℃, when the curing agent content increased from 0 to 0.2%, the permeability coefficient decreased from 93.410-7 cm/s to 810-7 cm/s, with a decrease of 91.4%; when the curing agent content increased from 0.2% to 0.4%, the permeability coefficient decreased from 810-7 cm/s to 1.1410-7 cm/s, with a decrease of 85.8%. At 10℃, when the curing agent content increased from 0 to 0.2%, the permeability coefficient decreased from 61.510-7 cm/s to 5.2710-7 cm/s, with a decrease of 91.4%; when the curing agent content increased from 0.2% to 0.4%, the permeability coefficient decreased from 5.2710-7 cm/s to 0.7410-7 cm/s, with a decrease of 86%. The possible reason of this situation is: firstly, the curing agent has the effect of thickening, the free water between the soil particles, and the formation of three-dimensional mesh structure, which significantly improves the viscosity of free water and suppresses the rate of water migration; secondly, the curing agent connects particles. The curing agent adsorbs on the surface of the soil particles, to narrow the particle spacing and block the native pore channel.

The effect of water-solid ratio on the permeability coefficient is shown in Figure 3. With the increase of water-solid ratio, the permeability coefficient of solidified soil is increasing, and the growth rate is faster and faster. At the test temperature of 25℃, the water-solid ratio increased from 0.40 to 0.50, the permeability coefficient increased from 0.5410-7 cm/s to 3.4810-7 cm/s, an increase of 544%; the water-solid ratio increased from 0.50 to 0.60, and the permeability coefficient increased from 3.4810-7 cm/s to 34.810-7 cm/s, an increase of 900%. At the test temperature of 10℃, the water-solid ratio increased from 0.40 to 0.50, and the permeability coefficient increased from 0.3510-7 cm/s to 2.2910-7 cm/s, an increase of 554%; the water-solid ratio increased from 0.50 to 0.60, and the permeability coefficient increased from 2.2910-7 cm/s to 22.410-7 cm/s, an increase of 878%. The possible reason for this situation is that with the increase of water-solid ratio of 0.40-0.50, the increase of the free water and electrostatic attraction between the soil particles increases the spacing between soil particles. Meanwhile, excessive free water occupies the pore space, forms a continuous seepage channel, and decreases. During the 0.50-0.60, with the increase of the water-solid soil ratio, the free water between soil particles further increases and loses effective cementation, resulting in a sharp increase of permeability coefficient.

The influence of temperature on the permeability coefficient is shown in Figure 2 and Figure 3. Under the same conditions, the higher the temperature, the greater the permeability coefficient of the solidified soil. The permeability coefficient of 25℃, 25℃, 2.29 10-7 cm/s: 0.3% and 0.50:6 5.8% of 25℃, 0.60,34.410-7 cm/s of 25℃. The reasons for this phenomenon can be analyzed as follows: At 25 ℃, the early cement hydration reaction rate is relatively fast, resulting in the generation of large quantities of calcium aluminate crystals (AFt) and C-S-H gels. Because the faster reaction leads to an uneven distribution of the hydration products, local regions with microcracks form due to contractile stress, creating a preferential seepage path. This results in an increased permeability coefficient of the solidified soil. Conversely, at 10 ℃, the increased viscosity of the free water slows down the rate of free-water migration in the pores, reducing the effective permeability. Simultaneously, the early cement hydration reaction rate is relatively slow, allowing for a more uniform distribution of the hydration products. Consequently, the integrity of the solidified soil structure is enhanced, thus reducing the permeability coefficient.

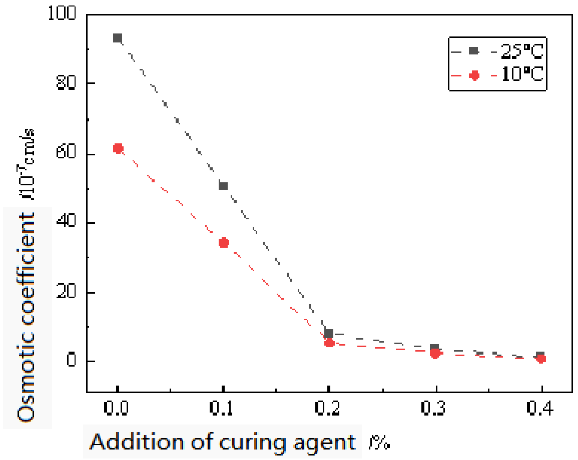

Figure 2 The influence of the curing agent dosage on the permeability factor

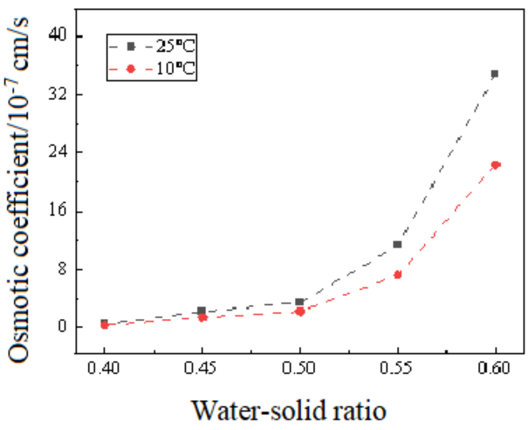

Figure 3. Effect of the water-solid ratio on the permeability coefficient

3.2 Unlimited compressive strength analysis

The effect of curing agent dosage on the unconfined compressive strength is shown in Figure 4, the curing soil without curing agent has the highest unlimited compressive strength (28d standard trophic strength is 898 kPa), indicating that the addition of excessive curing agent may interfere with the hydration reaction of cement and the formation of spatial network structure. With the increase of curing agent dosage (0%~0.4%), the unconfined compressive strength of curing soil shows a non-monotonic trend of first decreasing, then rising and then decreasing, in which the group with 0.3% curing agent dosage is the maximum value in the group containing curing agent. The standard autotrophic strength of curing soil of 0.1%, 0.3% and 0.4% of curing agent is 745 kPa, 821 kPa and 783 kPa, respectively. The reason for this possibility is that the dual mechanism of the curing agent on the cured soil. On the one hand, the curing agent absorbs the cohesion on the surface of the soil particles in the water, on the other hand, it hinders the formation and crosslinking of the cement hydration products, resulting in the decrease of the overall mechanical properties of the cured soil test block.

The effect of water-to-solid ratio on the unconfined compressive strength is shown in Figure 5, and the increase of water-solid ratio will significantly reduce the unconfined compressive strength of the solidified soil. The water-solid ratio increased from 0.4 to 0.6, the standard compressive strength of solidified soil 28d decreased from 1260 kPa to 420 kPa (66.7% decrease), and the standard compressive strength of solidified soil 28d decreased from 955 kPa to 401 kPa (58% decrease). The possible reason for this situation is that the increase of water-solid ratio increases the free water content between soil particles, weakens the cohesion between soil particles, and forms many pore channels, reducing the compactness of the material.

The effect of curing age on unconfined compression is shown in Figure 4 and Figure 5. Under the same curing agent content and the same water-solid ratio, with the increase of curing age, the unconfined compressive strength of solidified soil water cultivation and standard breeding is increasing. The 3d standard compressive strength of 0.1-0.50 was 229 kPa, 28d standard was 745 kPa, and the growth rate of 225.3%;0.4-0.503d standard was 248 kPa, 3d was 382 kPa, and 28d was 955 kPa, with a growth rate of 150%. The possible reason for this situation is that with the increase of maintenance age and the continuation of the cement hydration reaction, the calcium silicate (C-S-H) gel, calcium (AFt) and other products gradually fill the pores between the soil particles, forming a three-dimensional spatial network structure, significantly improving the material density and the cohesion between soil particles. In addition, the curing agent also has certain water retention properties, which can delay the evaporation of water and promote the moisture reaction in the later stage, thus significantly improving the density of the material and the bonding strength between the soil particles.

As shown in Figure 4 and Figure 5, the water trophic strength is lower than that of standard standard under the same curing agent and the same water-solid ratio. The 28d standard standard of 0.4-0.50 was 783 kPa, 535 kPa, 68.3%;0.2-0.50764 kPa, 28d 6 30 kPa, and 82.5% of the standard. The possible reason for this situation is that the dissolution or precipitation of the cement hydration products can destroy the formed spatial network structure; under the water storage condition, the pores between the soil particles are occupied by free water, forming a connected channel and reducing the compaction of the curing soil.

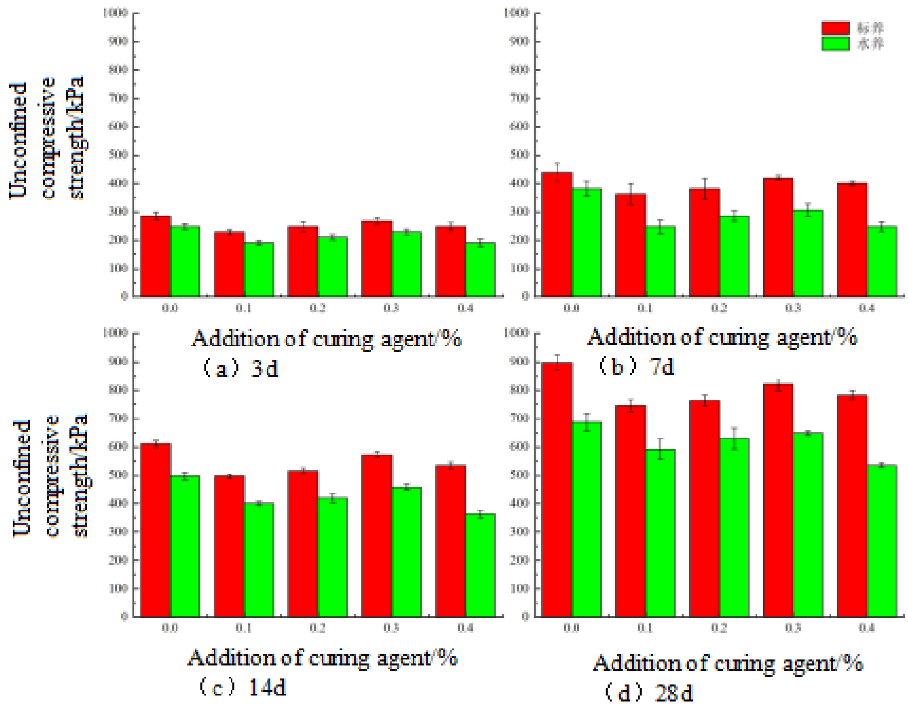

Figure 4. Effect of the curing agent dosage on the compressive strength of the cube

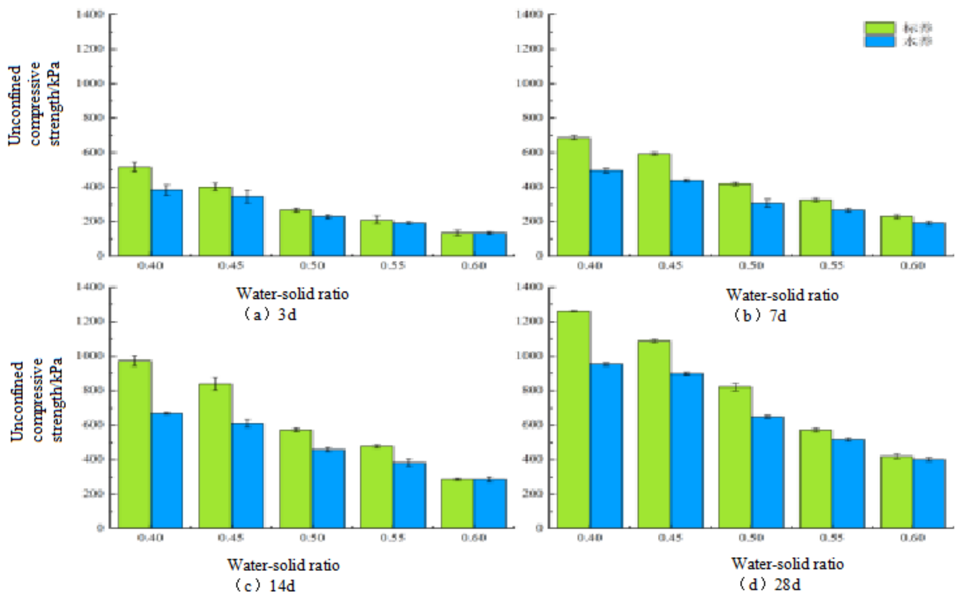

Figure 5. Effect of water-solid ratio on the compressive strength of the cube

3.3 Analysis of the bleeding rate

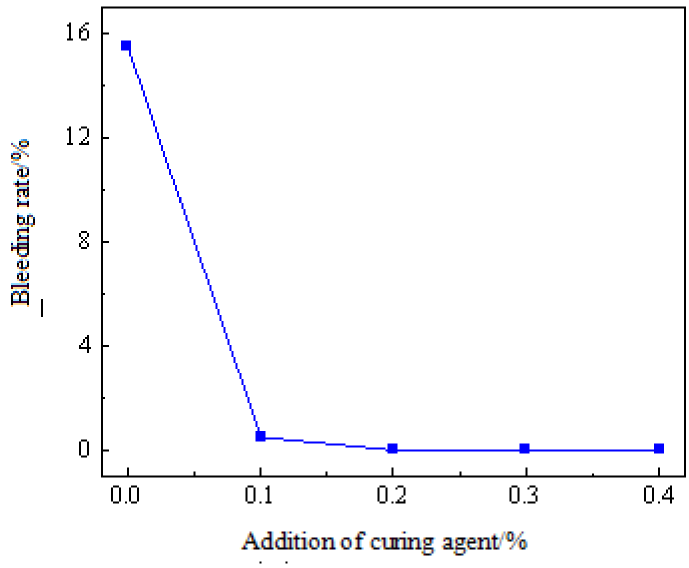

Figure 6 Effect of curing agent dosage on bleeding rate

The effect of curing agent dosage on the bleeding rate is shown in Figure 6. In the range of 0~0.1%, with the increase of curing agent dosage, the bleeding rate of curing soil decreases sharply. When the curing agent mixture was 0%, the bleeding rate was 15.5%, and when the curing agent mixture was increased to 0.1%, the bleeding rate was 0.5%, with a decrease of 96.8%. The possible reason for this is that the curing agent solves in the free water between the soil particles, forming a dynamic three-dimensional colloidal network structure, which significantly improves the viscosity of the liquid phase and inhibits the rise of water. When the amount of curing agent exceeds 0.2%, the bleeding rate of cured soil is always 0%. The reason for this is that excessive curing agent is dissolved in free water between the soil particles, forming a dense gel layer, completely sealing the capillary pore and blocking the path of water migration.

The effect of water-solid ratio on the drainage rate is shown in Figure 7. When the amount of curing agent is set at 0.3%, the water-solid ratio changes within the range of 0.4~0.6, and will not affect the bleeding rate of cured soil, and the bleeding rate is always zero. The possible reason for this is that the curing agent solves in the free water between soil particles, forming a dynamic three-dimensional colloidal network structure, which significantly improves the viscosity of the liquid phase. Even with the increase of water-solid ratio, the free water between soil particles increases, it is difficult to dilute the concentration of thickening agent to the critical value of bleeding water concentration.

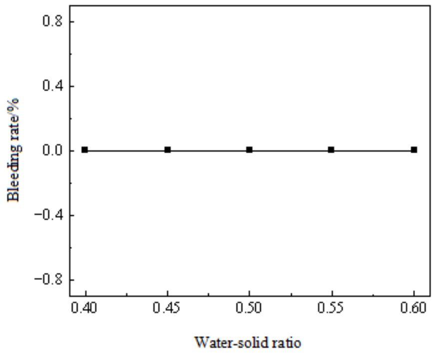

Figure 7 Effect of water-solid ratio on bleeding rate

4. Conclusion

This paper carries out permeability coefficient test, cube test and drainage rate test for red clay in Chongqing, and studies the influence of curing agent content and water-solid ratio on the above test results, and mainly draws the following conclusions:

The increase of the impermeability of cured soil is the mechanism of curing agent dissolved in the free water between soil particles, forming a dynamic three-dimensional mesh structure, inhibiting the migration of free water and hindering the seepage channel; the increase of water-solid ratio will weaken the impermeability of the cured soil, the increase of free water will weaken the particle bonding and form the seepage channel; the temperature increase will promote the hydration reaction of cement, leading to the uneven distribution of hydration products and the decrease of microcracks.

In terms of mechanical properties, due to the dual action of the curing agent, the optimal value; the increase of water-solid ratio will weaken the bonding between soil particles and reduce the compaction, thus significantly reducing the unconfined compressive strength; with the increase of maintenance age, cement hydration further fills the pores between the soil particles, forming a three-dimensional network structure, enhancing the integrity and compaction of the soil, thus increasing the compressive strength; in addition, when the hydration strength is lower than the standard trophic strength.

Water performance, when curing agent dosage 0.2%, curing agent in the free water channel between soil particles inside a dense gel layer, closed pores, block water migration, makes the bleeding rate to zero, water-solid ratio in 0.4~0.6 change of bleeding rate, indicating that curing agent colloidal network of free water dilution has strong resistance.

References

[1] Wu Wenpeng, Xu Lang, Zhang Chao, et al. Analysis of timely variable vulnerability of bridge foundation erosion risk based on probabilistic hydrological information [J]. Journal of Natural Disasters, 2024,33 (06): 151-161.

[2] Chen Hu, Xu Jieliang, Chen Qigang, et al. Study on the most unfavorable pier position of unequal parallel bridge [J]. Highway Traffic Technology, 2024,41 (04): 99-109.

[3] Xiong Wen, Cai Chunsheng, Zhang Rongzhao. Review of bridge flooding studies [J]. Highway Journal of China, 2021,34 (11): 10-28.

[4] Deng L, Cai C S. Applications of fiber optic sensors in civil engineering[J]. Structural Engineering and Mechanics, 2007, 25(5): 577-596.

[5] Xiong W, Cai C S, Kong X. Instrumentation design for bridge scour monitoring using fiber Bragg grating sensors[J]. Applied Optics, 2012, 51(5): 547-557.

[6] Deng L, Cai C S. Bridge scour: Prediction, modeling, monitoring, and countermeasures[J]. Practice periodical on structural design and construction, 2010, 15(2): 125-134.

[7] Li Zhiyue, Dai Guoliang, Du Shuo, et al. Experimental study on flow state solidified soil erosion resistance characteristics of offshore wind power foundation [J]. Journal of Southeast University (Natural Science Edition), 2023,53 (4): 647-654.

[8] Wei Song, She Haiqiang, Wu Yonggang, et al. Study on local scour of piers under protection of retaining ring and stone age structure [J]. Journal of Hefei University of Technology (Natural Science Edition), 2024,47 (12): 1721-1728.

[9] Mohammed Y A, Saleh Y K, Ali A A M. Experimental investigation of local scour around multi-vents bridge piers[J]. Alexandria Engineering Journal, 2015, 54(2): 197-203.

[10] Wang Haiyu, Shen Kanmin, He Rui, et al. Impact of seabed reinforcement on the dynamic characteristics of single pile foundation of offshore wind power [J]. Journal of Solar Energy, 2024,45 (06): 607-618.

[11] Yan Zhengyu, Tian Hua, Kang Wen, et al. Study of foundation scour protection of building structures in water [J]. Marine, 2022,44 (02): 150-156.

[12] Zhang Zongfeng, Ding Hongyan, Liu Jinkun. Application of concrete interlocking row in erosion protection of submarine pipeline [J]. Ocean Engineering, 2015,33 (02): 77-83.

[13] Zhao Hanyan, Le Shaolin, Zhou Huan, et al. Analysis on hydrodynamic weakening and protection effect of neutral grid on local erosion of round pile [J]. Ocean Engineering, 2022,40 (05): 111-120.

[14] Su Yue, Yan Nan, Bai Xiaoyu, et al. Research progress and application of engineering characteristics of ready-mixed liquid-cured soil [J]. Material Guide, 2024,38 (9): 66-72.

[15] Wang Qiusheng, Xiu a soldier, Qi Yunpeng, and so on. Curing mechanism and anti-erosion characteristics of cement cured soil [J]. News of Yangtze Academy of Sciences, 2024,41 (8) 142-149.

[16] Du Shuo. Research on local scour characteristics and protection of solidified soil of single pile foundation of offshore wind power [D]. Southeastern University, 2021.

[17] Wang C, Yuan Y, Liang F, et al. Investigating the effect of grain composition on the erosion around deepwater foundations with a new simplified scour resistance test[J]. Transportation Geotechnics, 2021, 28: 100527.

[18] And Qingdong, Qi Jiangong. Application of a new technology in erosion protection of offshore fan foundation [J]. Southern Energy Construction, 2020,7 (02): 112-121.

[19] Yuan Jianzhong. Application of solidified soil in scour repair of single pile foundation of offshore wind power [J]. China Marine Platform, 2021,36 (4): 46-50.

[20] Ding Jian, Xie Jinbo, Wang Jing, et al. Research and application of in-situ silt curing technology in anti-erosion of single pile foundation of offshore wind power [J]. Harbor Construction of China, 2022,42 (8): 18-21.

[21] Zhou Maoqiang, Li Peng, Luo Xianqi, et al. Application of solidified soil in the scour protection engineering of offshore wind power foundation [J]. Waterway and port, 2023,44 (2): 264-269.

[22] Li Tengfei, Zhang Guanwu, Chen Jiazhi. Study on the influence of silt solidified soil on single pile foundation of offshore fan [J]. Hydropower and New Energy, 2023,37 (05): 22-26 + 30.

[23] OuYang H, Dai G, Gao L, et al. Local scour characteristics of monopile foundation and scour protection of cement-improved soil in marine environment-Laboratory and site investigation[J]. Ocean Engineering, 2022, 255: 111443.

[24] Shen Xiaolei, Guo Jian, Zhang Haitao, et al. Research on the horizontal bearing characteristics of offshore wind power pile foundation reinforced by solidified soil [J]. Waterway and port, 2023,44 (1): 118-123.