Damage analysis of deep water high pile cap foundations under different concrete corrosion by ship impact load

Zhang Xuefeng
Research Institute of Highway Ministry of Transport, 100088, Beijing, China
28144484@qq.com

Abstract. The deep-water high-pile cap foundation is in the water environment for a long time, which is likely to cause corrosion damage to the pile foundation concrete. At present, the damage analysis of the upper structure has received more attention and the technology is relatively complete, but the research on the damage identification and analysis of the substructure and foundation relatively lacking. Due to the loading characteristics of the substructure, its own bearing characteristics and the geological watermark environment, which are quite different from the upper structure, the corresponding damage identification and damage analysis evaluation technology is quite different from that of the upper structure, so special research is needed.

1. Introduction

With economic development, increasing demand for transportation and continuous improvement of bridge construction technology, a large number of river-crossing bridges at home and abroad have emerged one after another. High-pile caps have the advantages of convenient construction and saving engineering costs and are widely used by cross-river-sea bridges, which causes the deep-water high-pile cap foundation to be in a water environment for a long time. The foundation structure of deep-water high-pile caps is flexible, and it is easily damaged by the influence of foundation erosion and water medium dynamics [1], [2]. Effective damage analysis has always been a difficult point for the healthy and safe operation of the cross-river-sea bridge. According to the available data, there are two main types of foundation diseases and damages of bridges across rivers and seas according to their causes [3]. One is durability diseases caused by environmental influences of materials, such as apparent diseases such as steel corrosion, erosion, and biological corrosion; Force damage, such as earthquake, impact, wind and wave impact, etc., causes excessive force on the structure, causing concrete cracking, local damage and internal damage. The durability diseases of concrete in water are mainly manifested in the corrosion of steel bars, and the swelling, bulging, cracking, and detachment of concrete caused by corrosion [4]. There are also concrete crisping, surface shedding and water erosion caused by freezing and thawing, water and salt erosion. Diseases such as biological corrosion [5]. With regard to concrete corrosion in marine environments, scholars at home and abroad have conducted extensive and detailed experimental and theoretical studies. As far as the research scope is concerned, it mainly includes: the corrosion mechanism of steel reinforcement in concrete in marine environment, the corrosion rate of steel reinforcement in concrete, the detection method of steel corrosion, the protection method of steel corrosion, the mechanical properties of steel after corrosion, the mechanical properties of concrete after steel corrosion [6]. The influence of corrosion on the performance of concrete structures, the resistance evaluation of reinforced concrete structures or components, and the prediction of structural durability life [7]. Through the efforts of many domestic
and foreign scholars, the research in the above-mentioned fields has achieved fruitful results, and a more in-depth understanding and understanding of the corrosion of steel bars in concrete in the marine environment has been obtained. Many research results have begun to be used in actual structures and have achieved good results [8].

2. Methods
Damage can be seen as various external factors, such as corrosion, load, humidity, etc. These micro-defects continue to cause, expand and integrate. The continuous distribution of micro-defects in the solid material or internal makes the material or structure degrade in performance. The rigidity and strength of the performance decrease, a large number of cracks, even breakage and failure. Reinforced concrete components in a seawater environment have different locations and conditions, and their corrosion mechanisms are different. Generally, we divide the marine corrosion environment into atmospheric areas, splash areas, tidal ranges, and seawater full-immersion areas. The main pier foundation damage of the cross-sea bridge mainly affects the safety performance of the foundation: concrete corrosion, concrete cracking, steel corrosion, and foundation erosion. This study uses concrete corrosion damage as an example to study structural damage indicators. Concrete corrosion is a common damage to pile foundations in seawater. The current situation of pile foundation corrosion of a coastal bridge is shown in Figure 1.

Figure 1. The corrosion status of a coastal bridge pile foundation

Seawater contains a lot of chlorides, which is highly corrosive to steel in the marine environment. Chloride ion corrosion is the main cause of steel corrosion in concrete. Concrete is composed of pores and coarse aggregate volume of cement mortar. In the concrete mixing system, in order to obtain the necessary workability, more water is added than the water-cement ratio [9]. This part of the water is retained in the concrete with free water. As the temperature decreases, the pore water begins to freeze and expand. The volume expansion is a degree of wet saturation, cement slurry penetration, the nearest pore distance, cooling rate and retention. After the temperature, when the stress exceeds the tensile strength of concrete, local cracks may occur and the strength of concrete decreases [10]. After repeated freezing and thawing cycles, the damage of concrete will continue to increase and the strength will gradually disappear. In the marine environment, the concrete is completely immersed in water or under high humidity conditions. Due to the high degree of water permeability, the freezing and thawing cycle of concrete is longer than the general atmosphere due to the long-term heat caused
by sea water. The environment is serious. In addition, the internal cracks and surface cracks of concrete during freezing and thawing cycles are more easily penetrated by carbon dioxide and chloride ions, thereby accelerating the corrosion of steel bars.

3. Concrete damage constitutive relationship

The nonlinear mechanical behavior of concrete includes the influence of microcracks and plastic flow of these two types of microscopic mechanisms. Therefore, concrete materials have the following remarkable characteristics:

1. The existence of regional instability accompanied by significant stiffness degradation and softening after peak strength stress;
2. When the loading and unloading process of repeated concrete deformation exceeds a certain threshold, the unloading deformation is completely unrecoverable;
3. The strength and ductility of confined concrete increase significantly (such as the state of compressive biaxial stress);
4. Due to the tensile stress of the biaxial compressive strength of the lower concrete material, the tensile and compressive stress is higher than the uniaxial compressive strength, which is the so-called tensile and compression softening;
5. Unilateral effect: There is a significant difference between compressive strength and tensile strength, especially when the wound is pulled in a clear direction, the crack closure after the reverse tensile load will lead to the recovery of the stiffness of the concrete.

The reasonable damage constitutive relationship correctly describes the two different and irreversible processes of change. Since 1980, many scholars have begun to apply damage to the mechanical properties of concrete to study mechanics. The first job is to create specific experimental data for changes in the stress level of damage or pressure. This law is expressed by the following formula, usually called It is the damage model. At present, specific damage models have been established, mainly based on or uniaxial stress experiments, and semi-experimental and semi-empirical modeling methods are mostly adopted when establishing the model.

4. Simulation analysis

The North Channel Bridge of Hangzhou Bay Cross-sea Bridge is a double-tower, double-cable plane cable-stayed bridge. The main bridge is 908m in length, and the span combination is 70m+160m+448m+160m+70m. There are 26 bored piles with a diameter of 2.8m under each main pier, the average pile length is 125m, the bottom elevation of the pile is -125.800m, the diameter of the bored pile steel casing is φ3.1cm, the wall thickness is 20mm, and the bottom elevation of the casing is -43.500m. The cap is a hexagonal round and chamfered integral cap, the size of the cap is 48.5×23.7×6.0m, and the top elevation of the cap is +5.200m. Hangzhou bay bridge D13 pier model in Figure 2.

Figure 2. Hangzhou bay bridge D13 pier model
5. Results
In this study, the damage of the pier foundation under the load of each working condition is analyzed. The damage of the typical foundation (corrosion 15cm) is shown in Table 1, and the calculation and analysis of the bridge are shown in Figure 3 to Figure 6.

Table 1. Pier scouring case damage results

| position                  | Concrete compression damage (DAMAGEC) | Concrete Tensile Damage (DAMAGET) | Concrete vertical stress S33 (MPa) | Concrete plastic strain PE | The maximum tensile stress of steel bars (MPa) | Horizontal displacement of the tower (cm) |
|---------------------------|--------------------------------------|-----------------------------------|-----------------------------------|----------------------------|-----------------------------------------------|------------------------------------------|
| Cross beam in the top surface | 0.00                                 | 0.00                              | --                                | 0.00                       |                                               |                                          |
| Cross bar bottom          | 0.00                                 | 0.00                              | --                                | -1.57E-4                   |                                               |                                          |
| 1 # Pile top outside      | 0.00                                 | 0.39                              | -18.94                            | 0.00                       |                                               |                                          |
| 1 # Pole bottom outside   | 0.00                                 | 0.00                              | 2.36                               | 0.00                       | 162.00                                        | 6.56                                     |
| 13 # Pile top outside     | 0.00                                 | 0.00                              | 20.92                              | 0.00                       |                                               |                                          |
| 13 # Pole bottom outside  | 0.00                                 | 0.41                              | -13.18                             | 0.00                       |                                               |                                          |

Figure 3. Pier concrete S33 strain cloud
Figure 4. Pier concrete PE strain cloud

Figure 5. Main Pier DAMAGET cloud (whole idea)
The analysis results show that the cracking damage range of the bridge tower beams under the ship collision is larger than that under the wave action, the top and bottom of the pile foundation cracking damage, the damage of the pile foundation corrosion damage area further expands, and the steel bar does not yield.

6. Conclusions
(1) The pier foundation of the bridge piercing 5cm under the action of the ship hit the bridge beam cracking damage, the top and bottom of the pile foundation under the local crack damage bridge pier beam damage cracking, the bottom of the pier, pile foundation and the bottom of a slight damage, Plastic strain, local cracking, rebar began to yield.
(2) Pier pier foundation corrosion in 15cm state in the ship collision load bridge beam appears more serious damage cracking, pier bottom, pile foundation at the top and bottom damage, plastic deformation, local cracking, steel yield.
(3) the pier foundation corrosion 30cm in the ship collision load bridge bridge pier serious damage cracking, the top and bottom of the pile foundation has a large area damage, plastic strain, local cracking serious, steel yield.
(4) The main displacement of the main pier foundation of the cross-sea bridge is mainly caused by the horizontal displacement of the pier top, and the buckling of the steel leads to the collapse of the structure.

7. Acknowledgments
This study was funded by Young Elite Scientists Sponsorship Program by China Association for Science and Technology. The authors thank the anonymous reviewers and the Editor for their constructive comments and advice, which greatly improved the quality of this paper.

8. References
[1] Wu, T., Qiu, W., & Wu, G. (2020). Fatigue Damage Evaluation of Pile-Supported Bridges under Stochastic Ice Loads. Advances in Civil Engineering, 2020.
[2] Li, C., Li, H. N., Hao, H., Bi, K., & Chen, B. (2018). Seismic fragility analyses of sea-crossing cable-stayed bridges subjected to multi-support ground motions on offshore sites. Engineering Structures, 165, 441-456.
[3] Xu, B., Wei, K., Qin, S., & Hong, J. (2020). Experimental study of wave loads on elevated pile cap of pile group foundation for sea-crossing bridges. *Ocean Engineering*, 197, 106896.

[4] Ti, Z., Wei, K., Qin, S., Mei, D., & Li, Y. (2018). Assessment of random wave pressure on the construction cofferdam for sea-crossing bridges under tropical cyclone. *Ocean Engineering*, 160, 335–345. doi:10.1016/j.oceaneng.2018.04.036

[5] Qinglai, F., & Yufeng, G. (2018). Effect of Reinforcement Ratio and Vertical Load Level on Lateral Capacity of Bridge Pile Foundations. *Polish Maritime Research*, 25(s3), 120–126. doi:10.2478/pomr-2018-0120

[6] Ti, Z., Zhang, M., Li, Y., & Wei, K. (2019). Numerical study on the stochastic response of a long-span sea-crossing bridge subjected to extreme nonlinear wave loads. *Engineering Structures*, 196, 109287. doi:10.1016/j.engstruct.2019.109287

[7] Xia, C., Ma, Q., Liao, Z., & Xia, H. (2018, July). Numerical Simulation of Ship Collision on RC Cap with Anti-collision Steel Box Barrier of Over-sea Bridge. In *The 28th International Ocean and Polar Engineering Conference*. International Society of Offshore and Polar Engineers.

[8] Sha, Y., Amdahl, J., Dørum, C., & Yu, Z. (2018). Numerical Investigation of the Collision Damage and Residual Strength of a Floating Bridge Girder. *Volume 11A: Honoring Symposium for Professor Carlos Guedes Soares on Marine Technology and Ocean Engineering*. doi:10.1115/omae2018-78728

[9] Aminoroayaie Yamini, O., Mousavi, S. H., Kavianpour, M. R., & Movahedi, A. (2018). Numerical modeling of sediment scouring phenomenon around the offshore wind turbine pile in marine environment. *Environmental Earth Sciences*, 77(23). doi:10.1007/s12665-018-7967-4

[10] Zhu, J., & Zhang, W. (2017). Numerical Simulation of Wind and Wave Fields for Coastal Slender Bridges. *Journal of Bridge Engineering*, 22(3), 04016125. doi:10.1061/(asce)be.1943-5592.0001002