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Study on safety early-warning model of bridge underwater pile foundations

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Abstract. The health condition of of deep water high pile foundation is vital to the safe operation of bridges. However, pier foundations are vulnerable to damage in deep water due to exposure to sea torrents and corrosive environments over an extended period. In this paper, combined with an investigation and analysis of the typical damage characteristics of main pier group pile foundations, we study the safety monitoring and real-time early warning technology of the deep water high pile foundations, we propose an early warning index item and early warning threshold of deep water high pile foundation by utilizing a numerical simulation analysis and referring to domestic and foreign standards and literature. First, we combine the characteristics of structures and draw on more mature evaluation theories and experience in civil engineering-related fields such as dam and bridge engineering. Then, we establish a scheme consisting of a Early Warning Index Systemand evaluation model based on the analytic hierarchy process and constant weight evaluation method and apply the research results to a project based on the Jiashao bridge in Zhejiang province, China. Finally, we verify the rationality and reliability of the Early Warning Index Systemof the Deep Water High Pile Foundations.

Keywords: early warning index; early warning threshold; evaluation method; safety monitoring; underwater pile foundations

1. Introduction

Due to the marine environment in which deep water high pile foundation are located, the durability of the bridge structure often varies (Zhang *et al.* 2020). Depending on local conditions, chloride in the marine environment gradually invades the concrete (He *et al.* 2021, Raheem *et al.* 2020). The papers (Zhang *et al.* 2020, Mottahedi *et al.* 2021, Liu *et al.* 2020) showed that when the chloride ion concentration in the concrete reaches a certain level, the passivation film formed on the surface of the steel bar in the highly alkaline environment of the concrete starts to decompose. This results in the loss of its protective effect and a galvanic cell reaction that leads to the corrosion of steel bars occurs. When corrosion occurs, these chloride ions become the conductive ions of the galvanic cell reaction, thereby accelerating steel bar corrosion (Guo *et al.* 2018, Kumar *et al.* 2020). Afgan and Naim (2010) research results showed that the collision of ships seriously threatens the safety of bridges across the sea channel. Ship collision and bridge damage cause huge direct losses and increase maintenance costs to bridges, passing vehicles, ships, staff, etc. They also cause

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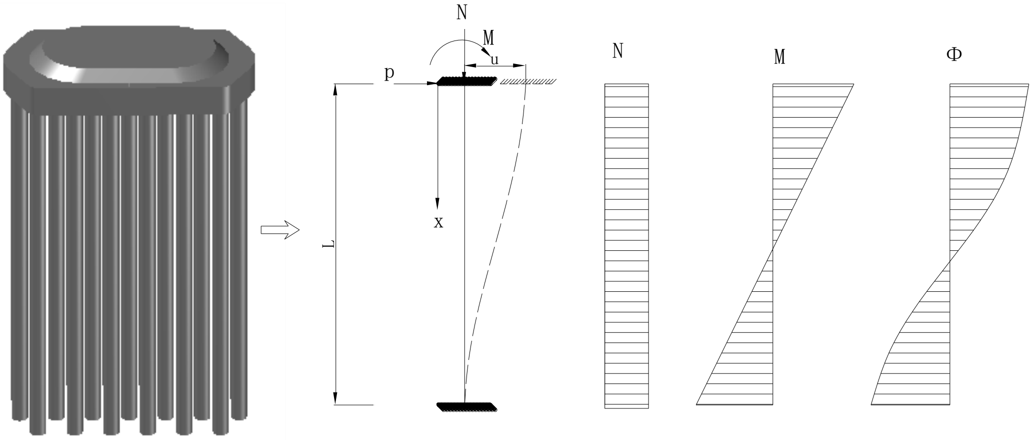

Diagrams of (a) pile group, (b) single pile foundation force, (c) axial force, (d) bending moment, (e) curvature

Fig.1 Diagram of internal force and curvature

significant indirect losses, such as traffic interruption and environmental pollution (Benedetti *et al.* 2018). Currently, bridge structure warning indicators are mainly focused on the upper structure, and there is relatively little research on underwater bridge pile foundations.

2. Mechanical performance analysis of single pile foundations of deep water high pile foundations

A single pile in deep water high pile foundation can be considered as a fixed constraint at both ends and is subjected to axial and horizontal forces. Figure 1 presents the internal forces and curvature diagram.

Under the action of a certain axial force N, the pile foundation is subjected to compression and bending deformation under the action of horizontal force. After making assumptions concerning the plane section, the relationship between internal force and stress of the section can be expressed as

$$\mathrm{N} = \int_A \sigma\, dA = \int_{A_c} \sigma_c\, dA + \int_{A_s} \sigma_s\, dA \tag{1}$$

$$\mathrm{M} = \int_A \sigma\, y dA = \int_{A_c} \sigma_c\, y dA + \int_{A_s} \sigma_s y\, dA \tag{2}$$

where A_c and A_s represent the cross-sectional areas of the concrete and the reinforcement.

The stress-strain relationship between the concrete and the reinforcement is

$$\sigma_c = E_c(\varepsilon) \tag{3}$$

$$\sigma_s = E_s(\varepsilon) \tag{4}$$

where ε denotes the strain, which can be obtained from the axial compressive strain ε_0 and curvature $\emptyset$, according to the following assumption regarding the plane section

$$\varepsilon = \varepsilon_0 - \emptyset y \tag{5}$$

In the elastic-plastic stage, we must perform the convergence calculation according to the nonlinear method, since the stress-strain relationship of the material is nonlinear.

3. Research on the early warning index system of deep water high pile foundations

3.1 Safety early warning index of deep water high pile foundations

(1) Early-warning evaluation indicators for the durability of deep water high pile foundation

Erosion by external aggressive ions to the interior of concrete is the primary factor that affects concrete durability (Sun *et al.* 2019, Benedetti *et al.* 2018). The papers (Xie *et al.* 2018, Blandon *et al.* 2018, Zhang *et al.* 2018) showed that Chloride ion corrosion is a critical issue that causes damage or even the structural durability failure of steel bars. Besides, the thickness of the protective layer reflects the ability of the concrete structure to resist chloride ion erosion (Lin *et al.* 2019). The corrosion of steel bars in concrete is an electrochemical corrosion process, and all factors affecting electrochemical corrosion have an impact on the corrosion rate of steel bars (Nazanin *et al.* 2019, Zhou *et al.* 2020). Of these influencing factors, concrete resistivity is one of the most significant factors that affects the corrosion rate of steel bars (Clive *et al.* 2018). Besides, damage to concrete in the sea is ultimately reflected in the corrosion of steel bars and the cracking of the concrete. Scholars (Mohammad *et al.* 2019, Zhang *et al.* 2018) showed that the corrosion potential of metals in different electrochemical states is substantially different.

To summarize, in this paper, we advocate that the main pier foundation durability early-warning evaluation indicators of sea-crossing bridges are mainly: ① chloride ion content of concrete in the sea C_{cl}; ② thickness of the concrete protective layer d; ③ concrete resistivity ρ; ④ steel corrosion potential U; ⑤ crack width w.

(2) Early-warning evaluation indicators for scour in deep water high pile foundation

When the foundation scour depth increases, the impact on the superstructure is negligible. However, the force on the lower structure, especially the structure of the pier foundation pile body, is relatively large. As the foundation scour depth increases, the pile foundation experiences more stress, which is disadvantageous (Seferoglou *et al.* 2018). Therefore, the foundation scour depth h can be used as an early warning evaluation index for the foundation scour of the main piers.

(3) Early-warning evaluation index of foundation settlement for the main piers of sea-crossing bridges

The role of bridge foundations is to transfer all the loads from the superstructure and the substructure to the foundation. For safe and regular bridge use, the foundations must have sufficient strength, stiffness, and overall stability. However, uneven settlement of pier foundations may adversely affect the stress of the superstructure. Therefore, the uneven settlement Δs of the main pier foundations can be used as an early warning evaluation index for the settlement of the main pier foundations.

(4) Early warning evaluation index for ship collision with deep water high pile foundation

According to the results of existing research, the degree of damage to deep water high pile foundation after ship collision can be quantitatively described by: ① crack width of the pile foundation w; ② strain on the steel bars and concrete ξ; ③ corner of the pile top θ.

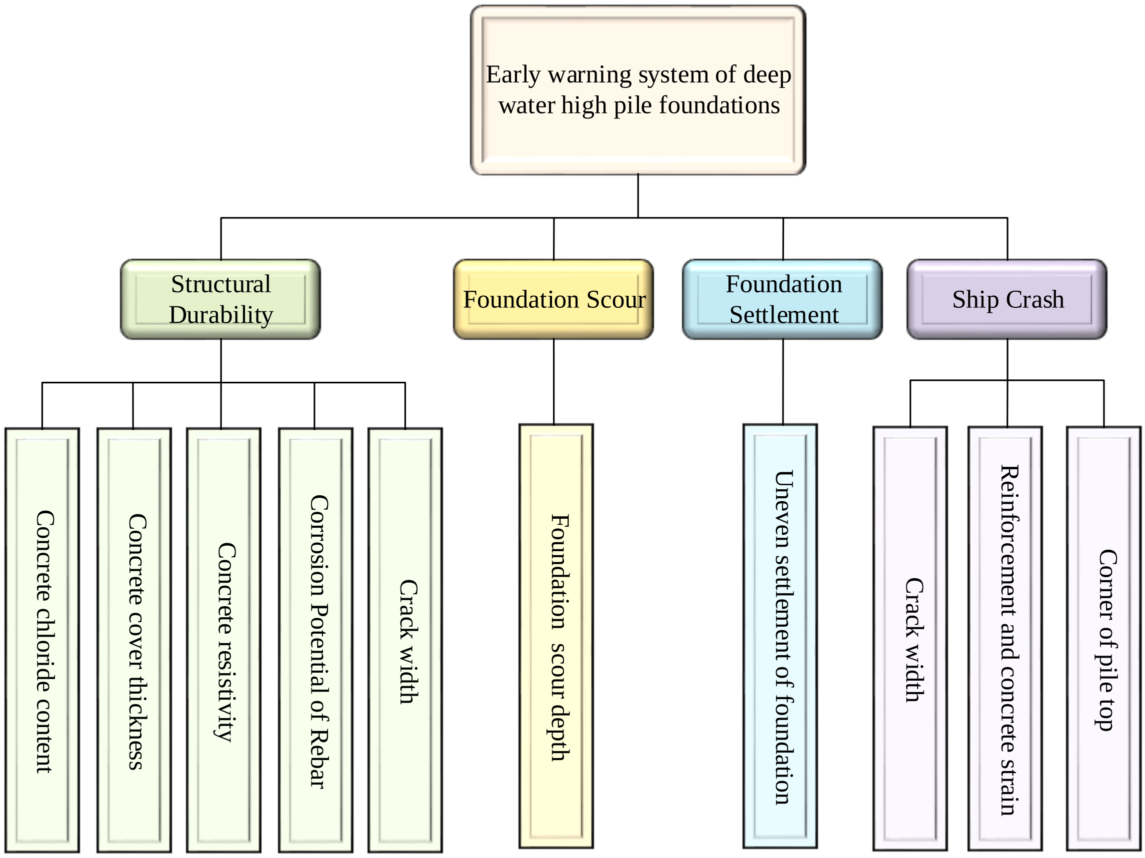

Fig. 2 Early warning indicator system

3.2 Early warning index system of deep water high pile foundations

Based on the analytic hierarchy process, we propose an early warning index system for the foundation safety of the main piers of sea-crossing bridges. This model contains four criteria layer indexes: structural durability, foundation scour, foundation settlement, and ship collision. The durability index also encompasses five indicators: concrete chloride ion content, concrete protective layer thickness, concrete resistivity, steel corrosion potential, and crack width. Fig. 2 presents a diagram of the system.

4. Early warning model of the main pier foundation for sea-crossing bridges

The structural early warning system aims to comprehend and master the state changes of structures by continuously performing simple data processes and statistical comparisons on monitoring information obtained by the system in real-time. This can promptly identify signs of possible disasters and provide maintenance staff and researchers with vital information. An alarm is raised so that the relevant department has enough time to confirm the likelihood of a disaster in a more comprehensive manner and take timely and effective measures to prevent the occurrence of the disaster or reduce losses caused by

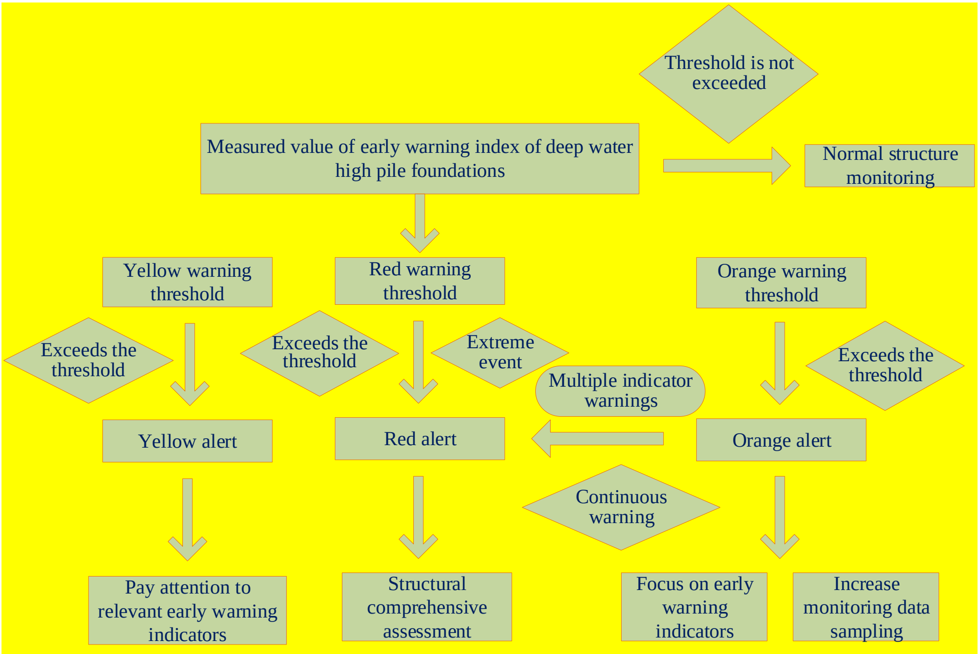

Fig. 3 Early warning model of Deep Water High Pile Foundations

the disaster. We propose this early warning model for deep water high pile foundation based on stress analysis of the main pier foundations, as Fig. 3 illustrates.

5. Engineering applications

5.1 Overview of the Jiashao Bridge project

The Jiashao Bridge has a total length of 10.137 km and is divided into six sections: the main channel bridge, north auxiliary channel bridge, approach bridge in the water area, approach bridge across the planned embankment, approach bridge across the embankment, and approach bridge in the land area. Among them, the main channel segment is a cable-stayed bridge with six towers, four cable planes, and framed steel box girders with a main span of 428 m. The foundation of the cable tower adopts a circular cap, and a 2.5 m-thick prismatic tower is set between the tower column and the cap. The Z4# ~ Z7# cable tower caps are 40.6 m in diameter and 6.0 m in thickness, and 32 bored piles with a diameter of 2.5 m are set under each cap. The Jiashao Bridge is shown in Fig. 4, and the main pier is shown in Fig. 5.

5.2 Engineering applications of the Jiashao Bridge

1. Early warning index setting

According to the early warning index system proposed in this paper, we established the early warning indexes of the main pier foundations of the Jiashao bridge as follows:

Fig. 4 Photograph of the Jiashao Bridge

Fig. 5 Main piers of the Jiashao Bridge

(1) Structural durability index: chloride ion content of concrete C_{cl}, thickness of concrete protective layer d, reinforcement corrosion potential U, structural cracks, and concrete resistivity ρ;

(2) Foundation scouring index: foundation scouring depth h;

(3) Foundation settlement index: uneven settlement of main pier foundations Δs;

(4) Foundation ship collision index: crack width of the pile foundation w, reinforcement and concrete strain ξ, pier top corner θ.

The method for determining warning indicators for other bridges is the same and can be referred to for implementation.

2. Early warning threshold setting

We set the threshold values of various early warning indicators for the main pier foundations of the Jiashao bridge as follows:

(1) Structural durability index

① Chloride ion content of concrete in sea C_{cl}

a) Normal state: C_{cl} < 0.15 (percentage of chloride ion content in concrete compared to cement content);

b) Yellow warning range: $0.15 \le C_{cl} < 0.7$;

c) Orange warning range: $0.7 \le C_{cl} < 1.0$;

d) Red alert range: $1.0 \le C_{cl}$.

② Thickness of concrete cover d

The bearing platform of the main piers of the Jiashao bridge is C30 concrete and the design thickness of the concrete protective layer is:

a) Normal state: $d > 0.95d_s = 76\ mm$;

b) Yellow warning range: $0.85d_s = 68\ mm < d \le 0.95d_s = 76\ mm$;

c) Orange warning range: $0.55d_s = 44m\ m < d \le 0.85d_s = 68\ mm$;

d) Red alert range: $d \le 0.55d_s = 44mm$.

③ Concrete resistivity ρ

a) Normal state: $\rho \ge 200\ k\Omega \cdot mm$;

b) Yellow warning range: $100\ k\Omega \cdot mm \le \rho < 200\ k\Omega \cdot mm$;

c) Orange warning range: $50\ k\Omega \cdot mm \le \rho < 100\ k\Omega \cdot mm$;

d) Red alert range: $\rho < 50\ k\Omega \cdot mm$.

④ Reinforcement corrosion potential

a) Normal state: $U \ge$ -200 mV;

b) Yellow warning range: -200 mV < $U \le$ -300mV;

c) Orange warning range: -300 $mV < U \le$ -500 mV;

d) Red alert range: U < -500 mV.

(2) Foundation scouring index

The Jiashao bridge is located in the Jianshan reach, which has a wide and shallow riverbed, strong tide, rapid current, turbulent tide bore, large tidal range, and strong fluctuation tidal current speed. The tidal current velocity can reach 8 m/s and the tidal range can exceed 9 m. Based on existing measured data and design standards, we conducted relevant model tests and established that the maximum scouring depth of the main pier of the main navigation hole can reach 27.8 m. Therefore, we propose a threshold value for the scouring early warning index of the main pier foundations of the Jiashao bridge as follows:

a) Normal state: $h \le 0.95h_d = 26.5\ m$;

b) Yellow warning range: $0.95h_d = 26.5\ m < h \le 1.0h_d = 27.8\ m$;

c) Orange warning range: $1.0h_d = 27.8\ m < h \le 1.1h_d = 30.5\ m$;

d) Red alert range: $h > 1.1h_d = 30.5\ m$.

(3) Foundation settlement index

Differential settlement between the main pier foundations of the cable tower is allowed in the pier foundation design of the Jiashao bridge, and the foundation settlement index threshold is set as follows:

a) Normal state: $\Delta s < 0.95\Delta s_d = 1.9\ cm$;

b) Yellow warning range: $0.95\Delta s_d = 1.9\ cm \le \Delta s < \Delta s_d = 2.0\ cm$;

c) Orange warning range: $\Delta s_d = 2.0\ cm \le \Delta s < 1.4\Delta s_d = 2.8\ cm$;

d) Red alert range: $\Delta s \ge 1.4\Delta s_d = 2.8\ cm$;

(4) Basic ship collision index

① Crack width w

a) Normal state: $w \leq 0.1\ mm$ (essentially no cracks);

b) Yellow warning range: $0.1\ mm < w \leq 0.15\ mm$ (cracks occur, but the crack width is not large);

c) Orange warning range: $0.15\ mm < w \leq 0.2\ mm$ (the concrete continues to crack and the crack width exceeds the standard);

d) Red alert range: $w \geq 0.2\ mm$, (the concrete is seriously cracked and the crack width far exceeds the standard).

② Strain of reinforcement and concrete ξ

In the construction of the bearing platform of the main pier foundations, C30 concrete was employed. Besides, the primary reinforcement of the main pier foundation was HRB335 reinforcement. The strain threshold settings of reinforcement and concrete are:

a) Normal state: $\varepsilon_{son} < \varepsilon_{sn} = 0.0033,\ \varepsilon_{te} < \varepsilon_{sy} = 0.001675;$

b) Yellow warning range: $\varepsilon_{son} > \varepsilon_{sn} = 0.0033,\ \varepsilon_{te} < \varepsilon_{sy} = 0.001675$ (cracks occur, but the reinforcement is far from yielding);

c) Orange warning range: $\varepsilon_{son} >> \varepsilon_{sn} = 0.0033,\ \varepsilon_{te} \leq \varepsilon_{sy} = 0.001675$ (serious cracking of the concrete occurs and the reinforcement strength is close to the yield point strength);

d) Red alert range: $\varepsilon_{son} >> \varepsilon_{sn} = 0.0033,\ \varepsilon_{te} > \varepsilon_{sy} = 0.001675$ (the concrete is seriously cracked and the strength of the reinforcement is greater than its yield strength).

Note: ε_{son} refers to the tensile strain of the concrete, ε_{sn} denotes the ultimate tensile strain of concrete; ε_{te} represents the tensile strain of the reinforcement, and ε_{sy} is the yield strength of reinforcement. The symbol > indicates that the exceeded value is not very large, while >> indicates that the value is far beyond the reference level.

③ Pile top corner θ

The cable towers of the Jiashao bridge adopt a single-column cable tower arrangement. The lower and middle tower columns are ordinary reinforced concrete structures, the upper tower column and bracket are fabricated from prestressed concrete, and the tower column utilizes a hollow box section. According to the requirements of stress and overall stiffness, the cable tower is equipped with a box section "X" support bracket. Through calculations and analysis, the threshold value of the early warning index for the pier top corner of the main pier foundation is:

a) Normal state: $\theta < \theta_s = 6.4 \times 10^{-4}$ (the pier top corner does not reach the first critical corner);

b) Yellow warning range: $\theta = \theta_s = 6.4 \times 10^{-4}$ (the pier top corner has just reached the first critical corner);

c) Orange warning range: $\theta_s = 6.4 \times 10^{-4} < \theta < \theta_d = 1.0 \times 10^{-3}$ (the pier top corner is between the first critical corner and the second critical corner);

d) Red alert range: $\theta_d = 1.0 \times 10^{-3} < \theta < 5\theta_d = 5.0 \times 10^{-3}$ (the pier top corner is greater than the second critical corner but less than five times the second critical corner).

6. Conclusions

Based on an investigation of relevant literature from around the world and relying on the engineering application verification of the Jiashao bridge, we obtained the following key results:

(1) According to measured data related to the main pier foundations of domestic sea-crossing bridges, we determined early warning index items and early warning threshold values of main pier foundations through numerical simulation analysis. Examples include the early warning index and early warning threshold value of the main pier foundation settlement as well as the early warning index and early warning threshold value of main pier foundation scouring.

(2) Combined with the characteristics of the structure and based on the analytic hierarchy process and constant weight evaluation method, we incorporated the concept of the medical grading of patient health evaluation into the evaluation of safety characteristics of Deep Water High Pile Foundations. Subsequently, we established an approach consisting of a Early Warning Index Systemand an early warning model.

(3) By utilizing the Jiashao bridge as an application example, we verified the Early Warning Index Systemand early warning model of deep water high pile foundation proposed in this paper.

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