

# Mechanical Analysis of Concrete Piers of Cross Sea Bridges under Freezing and Thawing Cycle Conditions and Wave Effects

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**Abstract.** In high latitude areas, cross sea bridges are mainly subjected to freeze-thaw cycles and wave effects. However, due to the combined effects of wave and freeze-thaw cycles, there is not much mechanical analysis on the mechanical properties of cross sea bridge piers, and it is impossible to further strengthen the protective measures of concrete bridge piers fundamentally. Therefore, this paper using ABAQUS software, establishes a concrete bridge pier model and applies wave forces of different sizes to obtain the deformation and stress situation of the model. The model exhibits significant contraction in the middle and upper parts of the bridge pier due to the wave force. Due to the contraction, the axial length of the upper part increases, and the contraction amplitude at the bottom is not significant. A circular arc transition forms during the transition stage. In the significantly contracted part, the strain component increases with ground height, while the stress component initially increases and then decreases with ground height. In the base section, the strain stress components decrease first and then increase with the increase of ground height. The relationship between stress and strain components and wave force loads is that both stress and strain increase with the increase of wave force. Through the research results of this paper, it can optimize the design structure of concrete bridge piers, save costs, and improve safety. At the same time, this paper also summarizes several strengthening measures for concrete bridge piers to improve the durability of concrete.

**Keywords:** Cross sea bridge, wave action; freeze-thaw cycle, Concrete bridge piers.

## 1. Introduction

At present, a large number of scholars at home and abroad have conducted numerical model analysis and experiments on the mechanical properties and prevention measures of various types of concrete under freeze-thaw cycles and wave action. The research content includes freeze-thaw cycles or wave-induced cross sea bridges, which are important components of the transportation network. Cross sea bridges are not only transportation projects but also important infrastructure for promoting regional development and national progress. However, cross sea bridges are subjected to wave, tidal, seismic, freeze-thaw cycles, and various physical and chemical effects in the marine environment, resulting in complex stress situations. Especially in high latitude areas, the piers of cross sea bridges will be more affected. Because the winter temperature in this area is relatively low, seawater will form ice formation. In spring, when the temperature rises, seawater will melt. So the piers of the cross sea bridge are greatly affected by freeze-thaw cycles in high latitude areas. The freeze-thaw cycle is when seawater enters the interior of the bridge pier structure through the pores in the concrete above 0 °C. Below 0 °C, seawater freezes, expands in volume, and generates expansion force. After a period of cycling, the interior of the structure is damaged, resulting in cracks in the structure. The occurrence of freeze-thaw cycles significantly reduces the material parameters and mechanical properties of concrete, consequently affecting the service life of cross sea bridges in marine environments. In addition, wave action is also the most common force in marine engineering. When wave intensity is high, it can have an impact on marine engineering, such as the movement and damage of concrete bridge piers, carrying a large amount of sediment and siltation. So, under the dual effects of freeze-thaw cycles and wave action, the safety of cross sea bridges cannot be ignored. Therefore, it is

extremely important to study the mechanical analysis and strengthening measures of cross sea bridges under wave action under freeze-thaw cycles.

Analyze the mechanical properties of various types of concrete to provide a basis for the safe construction of cross sea bridges. Teng Fei [1] conducted experimental research and numerical simulation to explore the mechanical properties of concrete under seawater freeze-thaw cycles and the seismic performance of concrete bridge piers. It was found that under the conditions of seawater freeze-thaw cycles, concrete bridge piers have a maximum freeze-thaw depth, providing direction for seismic response analysis of offshore bridges in cold regions. He Tao et al. [2] established a numerical model using ANSYS to explore the stress failure of freeze-thaw ice-water interface bridge piers. They found that the combination of upper load and static ice pressure caused shear failure of bridge piers. Increasing the diameter of the pier column, improving concrete strength, and setting special protective measures can be used to resist static ice pressure and protect concrete bridge piers to reduce damage. Li Xiangnan [3] simplified the wave load into a fatigue load test on bridge piers, obtained the axial compressive bearing capacity of bridge piers and the variation of other strains and fatigue loads, derived the formula for its bearing capacity, and verified it through experiments, providing a theoretical basis for future research. Xiao Liangzhou [4] found through experiments using CFRP and ESCC to reinforce concrete short columns that this reinforcement method can significantly improve the bearing capacity of concrete compression members, thereby enhancing the safety of concrete structures.

In summary, existing scholars have achieved certain results in the research of concrete under freeze-thaw cycles. However, there is currently limited research on the effect of wave action on concrete bridge piers under freeze-thaw cycles. This paper establishes a numerical model of concrete bridge piers under wave-breaking action using the ABAQUS finite element analysis method by referring to the material mechanical parameters under freeze-thaw cycle conditions that have been studied both domestically and internationally. The corresponding mechanical properties are obtained through the model. Finally, summarize the strengthening measures under the effects of waves and freeze-thaw cycles. The research in this paper is of great significance for the construction of cross sea bridges in high-latitude and cold regions of China.

## 2. Methods and Data

### 2.1. Data Source

The data used in this paper is sourced from Sun Lu [5]. These data were obtained by substituting the formulas and thermal conductivity equations derived by DUANA [6] into specific values. The formula of DUAN [6] is derived from the experimental summary and has a certain degree of accuracy. The data used in this paper includes a depth of 110mm from the concrete surface at the boundary between the freeze-thaw zone and the non-freeze-thaw zone, the size of the concrete bridge pier, a radius of 805mm, a height of 3000mm, an elastic model of 880MPa for plain concrete, a Poisson's ratio of 0.2, and constant transverse wave forces of 50KN, 100KN, and 150KN, respectively. Among them, the elastic modulus and Poisson's ratio generally represent the elastic properties of the material, and the calculation of constant transverse wave force is more convenient and has a certain representativeness.

### 2.2. Determination of Material Parameters for Bridge Piers Under Freeze-thaw Cycles

Under the action of freeze-thaw cycles, the number of freeze-thaw cycles is easy to calculate. Its impact on material properties is also relatively significant. In general, it is believed that the compressive strength of plain concrete is linearly related to the number of freeze-thaw cycles [5], which is convenient for calculation. The compressive strength of plain concrete decreases with the increase of freeze-thaw cycles [5]. DUAN et al. obtained the relationship between the elastic modulus of plain concrete and the number of freeze-thaw cycles through experiments [6], as shown in equations (1):

$$\frac{E_{cu}^F}{E_{cu}} = \exp(-1.1345 \times 10^7 f_{cu}^{-5.7089} N) \quad (1)$$

In the formula:  $E_{cu}^F$  is the elastic modulus (MPa) of plain concrete after multiple freeze-thaw cycles,  $E_{cu}$  is the elastic modulus of plain concrete before freeze-thaw cycles (MPa),  $f_{cu}$  is the compressive strength of plain concrete before multiple freeze-thaw cycles (MPa), and N is the number of freeze-thaw cycles.

This paper takes the elastic modulus of plain concrete after multiple freeze-thaw cycles with a service life of 100a as 880MPa.

In concrete bridge piers, the degree of freeze-thaw cycles varies with the depth [5]. The freeze-thaw depth of concrete can be calculated from the thermal conductivity equation (2).

$$\theta(d, t) = T_m + A_w \exp\left(-\sqrt{\frac{\pi}{\beta t_c}} d\right) \cos\left(\frac{2\pi}{t_c} t - d \sqrt{\frac{\pi}{\beta t_c}}\right) \quad (2)$$

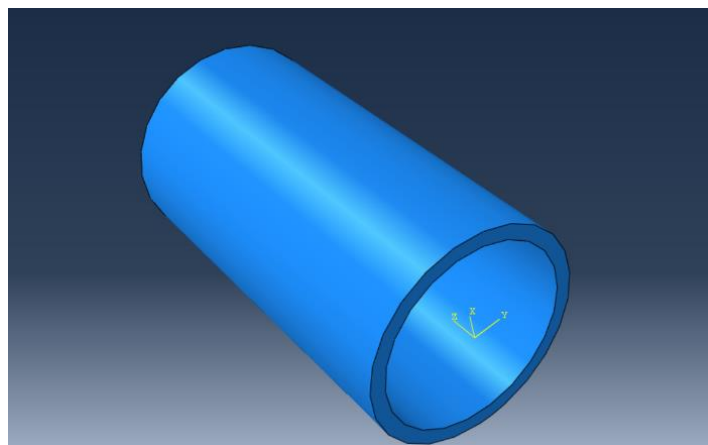
In the formula:  $T_m$  is the average temperature ( $^{\circ}\text{C}$ );  $A_w$  is the temperature difference on the surface of the component ( $^{\circ}\text{C}$ ),  $t_c$  is the temperature change period (h);  $\beta$  is the thermal diffusion coefficient ( $\text{m}^2/\text{s}$ );  $T$  is the time (h);  $D$  is the distance from the surface of the component (m);  $\theta(d, t)$  is the temperature ( $^{\circ}\text{C}$ ) at time  $t$  when the distance from the surface of the component is  $d$ .

In this paper,  $T_m = -0.5^{\circ}\text{C}$  is taken,  $A_w = 5^{\circ}\text{C}$ ,  $\beta = 6.15 \times 10^{-7} \text{ m}^2/\text{s}$ , from which it can be calculated that the boundary between the freeze-thaw zone and the non freeze-thaw zone is at a distance of 110mm from the concrete surface [5].

### 3. Numerical Simulation of Mechanical Parameters of Concrete Bridge Piers Under Wave Action Based on ABAQUS

Firstly, establish a model, as the central concrete column in the pier of the cross sea bridge is not subjected to freeze-thaw cycles [5]. Therefore, establish a hollow cylindrical model with a radius of 805mm, a ring thickness of 110mm, and a height of 3000mm.

Secondly, set the material parameters of the model. Concrete under freeze-thaw cycles is an elastic material with a modulus of 880MPa and a Poisson's ratio of 0.2 [5]. By inputting its parameters into the calculation model, the pier model of the cross sea bridge under freeze-thaw cycles is obtained (Fig.1).



**Fig. 1** Concrete Bridge Pier Model

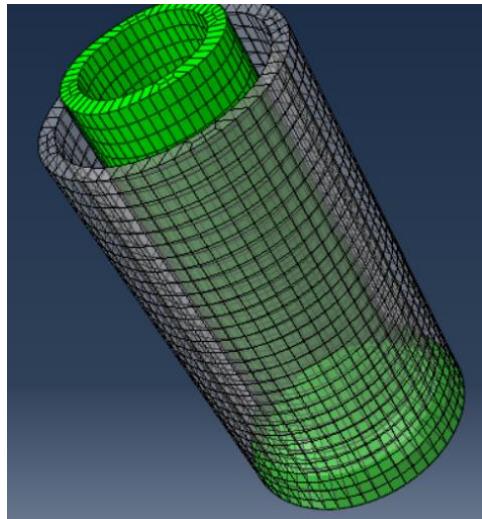
Finally, in the marine environment, the stress situation of the piers of cross sea bridges is complex. This paper ignores other forces and only retains wave forces. Due to the complexity of wave force calculation, the wave force will be further simplified. The lateral wave force was measured under experimental conditions with a clearance of 2 cm, a period of 1.5 seconds, and a wave height of 20 cm at an angle of attack of 0 degrees [7]. This paper takes its relatively stable lateral wave force, with values of 50, 100, and 150KN. Add initial boundary conditions.

## 4. Results and Discussion

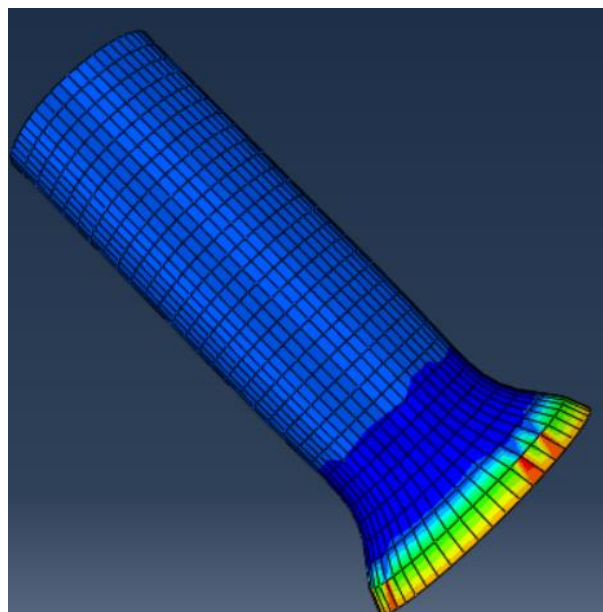
### 4.1. Analysis of the Relationship between Deformation and Stress Components and the Height of Bridge Piers from the Ground

Firstly, this paper mainly explores the distribution of deformation and stress components under increasing external forces. This paper mainly adopts three models for exploration, namely the models when the transverse wave force is 50, 100, and 150 KN. By continuously increasing external forces, it was found that the deformation state and stress-strain component distribution were the same, indicating that the deformation, strain component, and stress component of the bridge pier are independent of the magnitude of wave forces. Therefore, this paper only shows the model when the lateral wave force is 150 KN, as shown in Figure 2

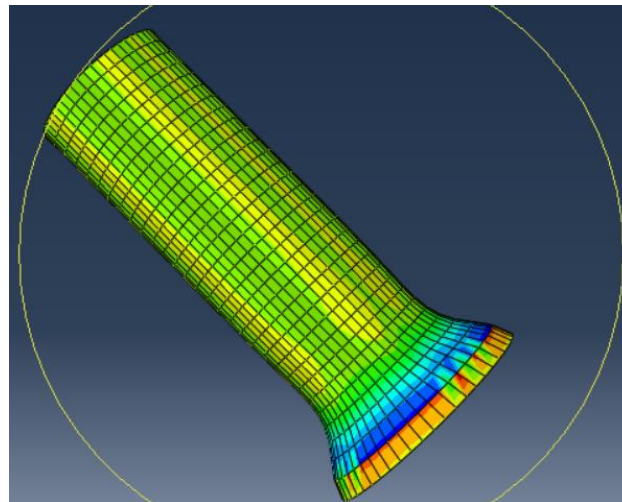
The gray part in Figure 2 represents the plain concrete model under only freeze-thaw cycles, while the green part represents the concrete model under freeze-thaw cycles and wave action. From Figures 3 and 4, it can be seen that the wave force causes a significant contraction in the middle and upper part of the bridge pier (911-3331mm in the Table 1). Due to the contraction, the axial length of the upper part increases, while the contraction amplitude at the bottom (135-557mm) is not significant, and the transition stage forms a circular arc transition.



**Fig. 2** Comparison between the initial model and the model after application



**Fig. 3** Strain Components



**Fig. 4** Stress Components

**Table 1.** Values of strain components with ground height

Wave forc  Height	3331	1999	911	557	224	135
50KN	92.0064	89.1281	84.5046	157.587	69.8323	264.627
100KN	184.013	178.256	169.009	315.175	139.665	529.254
150KN	276.019	267.384	253.514	472.762	209.497	793.881

**Table 2.** Values of stress components with height above ground

Wave forc  Height	3331	1999	911	557	224	135
50KN	371881	373065	338387	379111	153181	253538
100KN	743762	746129	676774	758222	306363	507706
150KN	1.11564e+06	1.11919e+06	1.01516e+06	1.13733e+06	459544	760614

Tables 1 and 2 show the relationship between strain and stress components and ground height. At 911-3331mm in the table, although the wave forces are different, the strain components gradually increase and the stress components first increase and then decrease. In the area of significant contraction, the strain component increases with the increase of ground height, while the stress component first increases and then decreases with the increase of ground height. At 135-557mm in the table, although the wave forces are different, the strain stress components first decrease and then increase. In the base section, the strain stress component decreases first and then increases with the increase in ground height.

Combining Tables 1 and 2 reveals that stress and strain components increase with the load. Vertically observing the chart from top to bottom, both strain and stress components show an increasing trend at all locations.

#### 4.2. Strengthening Measures of Concrete Under Wave Action and Freeze-thaw Cycle Action

According to the model analysis in the previous text, due to the significant shrinkage of stress in the concrete bridge pier, it is best to strengthen the concrete strength in the shrinkage part.

A Adopting new anchoring methods and optimizing structural design to enhance safety, stability, and future dismantling [8].

The bridge pier surface layer adopts fluorocarbon topcoat, the intermediate layer adopts epoxy resin intermediate paint, and the bottom layer adopts silane impregnation and epoxy sealing primer. Principle: Coating type anti-corrosion measures can isolate the infiltration and diffusion of harmful media such as chloride ions and acidic gases in concrete, and seal the pores and joints on the surface of concrete. The coatings used for the corresponding parts of the bridge piers mentioned above are summarized based on relevant specifications and engineering experience of Quanzhou Bay Cross Sea Bridge [9].

Optimize the concrete mix ratio and select concrete protective coatings with anti freezing properties to improve the durability of concrete. In high latitude cold regions, most of the damage to concrete is caused by freeze-thaw cycles, so antifreeze coatings are particularly important. The antifreeze coatings used should not fall off during freeze-thaw cycles and have strong frost resistance, even improving the frost resistance of concrete itself [10].

Using weather-resistant epoxy coating materials, new polyurea protective system coating materials, and unsaturated polyester resin materials. This helps increase the frost resistance of concrete. Through laboratory experiments, it was found that the surface protective coating of hydraulic concrete with epoxy adhesive as the primer and polyurea material as the topcoat has better frost resistance than unsaturated polyester resin material. The on-site production test results show that the new polyurea material has played a certain anti freezing effect. Therefore, this material can provide a certain degree of durability for concrete [11].

Set up deflectors to prevent the impact of waves. Principle: Starting from Gerrard's theory, protective measures for setting guide plates were proposed, and the suppression effects of different positions and plate lengths were analyzed and compared [12].

## 5. Conclusion

This paper establishes a concrete bridge pier model by examining the range of influence of freeze-thaw cycles on concrete and the numerical values of Young's modulus and Poisson's ratio of concrete after freeze-thaw cycles on concrete bridge piers. Wave loads and constraint conditions are then applied to this model, and the final model is obtained. Based on the stress-strain situation of the model, summarize the reinforcement situation of concrete under the simultaneous action of freeze-thaw cycles and wave action, and finally review literature to summarize the research on reinforcement measures of concrete. The following conclusions are drawn from this paper:

Assuming that the wave load is a constant horizontal force, there is a significant contraction in the upper part of the bridge pier. Due to the contraction, the axial length of this part increases and the transverse width decreases. The strain component increases with the height of the bridge pier from the ground, while the stress component increases first and then decreases with the height of the bridge pier from the ground. Both increase with the increase of the load. There is a slight shrinkage at the bottom of the bridge pier, both of which decrease first and then increase with the height of the pier above the ground, and increase with the increase of load.

This paper introduces how to strengthen the durability of concrete by adopting measures such as strengthening partial concrete strength, new anchoring methods, optimizing structural design, adopting effective protective coatings, setting guide plates, using new strengthening materials for concrete layers, and optimizing concrete mix proportions.

The limitation analysis of this paper includes that the concrete bridge piers studied in this paper are limited to circular bridge piers and do not involve square bridge piers. This paper assumes the wave load as a constant force, and the analysis of the form of wave load variation is not comprehensive. The mechanical parameters of concrete under freeze-thaw cycles used in this paper were obtained under specific conditions.

In the future, models can be established to determine Young's modulus and Poisson's ratio of concrete after freeze-thaw cycles, not just based on the number of freeze-thaw cycles. It is also possible to complicate wave forces by setting them as a function equation acting on concrete after freeze-thaw cycles, which is closer to the real situation. This study can develop reinforcement measures for concrete bridge piers based on their specific stress conditions, fundamentally changing the structure. This not only saves reinforcement measures but also improves the safety of concrete bridge piers.

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