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Study on vertical bearing characteristics of pile group foundation considering damage

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Abstract: *Aiming at the change of mechanical properties of bridge pile group foundation under corrosion, Abaqus finite element software was used to establish a bridge pile foundation model for analysis. Based on the improved Najar damage theory, the theoretical derivation of the damage evolution parameters in the code is derived. The damage factor is derived. The corrosion of the pile foundation is simulated by the method of reducing the elastic modulus. The spalling thickness represents the corrosion degree of the pile foundation. The displacement and bearing capacity of the pile under load, as well as the axial force and friction resistance of the corner pile, side pile and center pile are studied. The results show that under the working load condition, the load sharing ratio of the corner pile is the highest, followed by the side pile, and the sharing ratio of the middle pile is the lowest. However, as the peeling thickness increases, the difference between the three gradually decreases. The vertical ultimate bearing capacity of pile foundation decreases with the increase of peeling thickness, while the vertical displacement of pile foundation increases with the increase of peeling thickness. Under the action of load, the corner pile first shows signs of damage. In the process of increasing load, the damage range of the central pile gradually expands and deepens due to the increase of the load borne by the central pile. Therefore, enough attention should be paid to the reinforcement of damaged pile group foundation caused by pile foundation corrosion.*

Keywords: *numerical simulation; corrosion; damage; load parameter -supporting characteristics*

1. Introduction

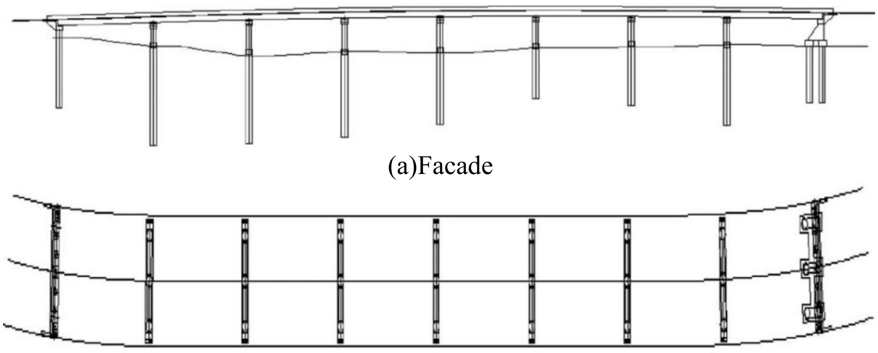
The problem of foundation wear and durability of bridge piles has always been widely valued by Chinese and foreign experts, mainly because of the corrosion of sodium sulfate and chloride salts. In some specific environments, chloride ions can reach the steel bar position through diffusion, capillary absorption and penetration through the cement protective layer, while the pile foundation in water is more susceptible to corrosion. Shang Minggang et al [1] constructed a model using saline soil as the transmission medium to simulate the deterioration of concrete under the common pressure of stable current and corrosive ions. Feng Zhongju et al. [2] found that the bearing capacity of the pile foundation gradually decreased after 8 years of use under the condition of dry and wet-freeze-thaw conditions in the Qinghai sea area, focusing on the protection of the pile foundation after 8 years of use.

There are many reasons for the corrosion of bridges. However, the erosion of chloride ions is the main factor leading to the corrosion of bridge pile foundations, which promotes the electrochemical reaction of steel bars. In this case, the corrosion of steel bars will lead to its volume expansion, resulting in internal stress, cracking and falling off of the concrete protective layer, which leads to the degradation of structural performance and reduces the mechanical properties of the structure [3]. Zheng et al. [4] studied that the ultimate bearing capacity of pile foundation will vary with the change of pile length under different corrosion depths. With the deepening of corrosion depth, the ultimate bearing capacity of pile foundation will gradually decrease. When the corrosion depth is constant, the increase of pile length will lead to the decrease of ultimate bearing capacity of pile foundation. Jin Weiliang et al. [5] studied the deformation of damaged concrete structure, analyzed the mechanical properties of concrete under corrosive environment and complex load, and put forward the development direction to be improved. Cen [6] compared and analyzed the seismic response law of bridge pile foundation under different conditions of corrosion or erosion, and found that corrosion had a great influence on the bending moment of bridge pile foundation, which provided a theoretical basis for the seismic performance of bridge in liquefied site [7]. Wu Qing et al. [8] discussed the influence of different corrosion methods on the mechanical properties of steel bars. The degradation of mechanical properties of steel bars becomes more and more obvious with the deepening of corrosion degree. Shi [9] deeply discussed the bearing capacity and deformation properties of pile group foundation under vertical load through static load test and numerical simulation analysis. The research shows that the properties of soil have a great influence on the bearing capacity and settlement of pile group. Li Jingpei et al. [10] studied the damage and deterioration mechanism of concrete structures in corrosive environments. Combined with the bearing characteristics of pipe piles and bored piles loaded in marine engineering environments, the degradation laws of their respective bearing characteristics were analyzed. Tian Hao et al. [11] pointed out that after the corrosion of reinforced concrete, the volume of steel bars will become larger, resulting in rust expansion force, which will cause the concrete to crack and fall off, resulting in lower concrete strength and lower bearing capacity of pile foundation, which may eventually lead to safety accidents.

In recent years, most scholars have studied the pile foundation corrosion of single pile and the bearing capacity of bridge pile foundation under the condition of pile group scour, but there are few studies on the pile foundation corrosion of pile group. Therefore, this paper establishes a three-dimensional numerical model of bridge pile foundation by Abaqus, and uses the reduced elastic modulus to simulate the corrosion degree of pile foundation. The purpose of this paper is to study the influence of different corrosion degrees on the erosion damage of bridge pile foundation, and to analyze the influence of corrosion degree on the vertical bearing characteristics of pile group under corrosion conditions. The research results provide a reference for the reinforcement design and construction of bridge pile foundation in the future.

2. Project profile

Taking an engineering bridge as an example, the vertical bearing characteristics of pile group foundation after damage are explored. The bridge has a total of 8 spans, divided into four spans, each span length of 30 meters, the bridge type is shown in Fig.1. The starting mileage pile number of the bridge is K2 + 332.1, the end mileage pile number is K2 + 593.779, the bridge center row is K2 + 464.3, and the bridge length is about 261.665 m. The surface water in the survey area is mainly the Lipu River, which flows through the site. The river is about 40m-100m wide and the water depth is 1m-4m. The pile group pile foundation of one span is taken for analysis, and the working conditions are divided as shown in table 1.



(a)Facade

(b)plane

Figure 1: Lipu East Ring Bridge

Table 1: Calculated work condition

working condition	Pile diameter D / m	Pile length / m	Stripping thickness d / cm
I	1	30	6
II	1	30	9
III	1	30	12
IV	1	30	15

ISSN 2663-1563 Vol. 7, Issue 1: 77-87, DOI: 10.25236/AJAGE.2025.070110

3. Numerical model and analysis

3.1 Concrete damage model (CDP)

The plastic damage model of concrete was proposed by foreign scholars Lubliner [12] and Lee and Fenves [13] in 1989.In many cases, especially under dynamic and cyclic loading, this model can better reflect the stress characteristics of materials than other models. Taking the stress-strain curve of C30 concrete as an example, the ' Code for design of concrete structures ' [14] GB 50010-2010 (2015 edition), Sidiroff energy equivalence principle [15], tension formula [16], Najar damage theory [17] and the change trend of damage factor used in this paper are drawn.As shown in Fig.2 and Fig.3

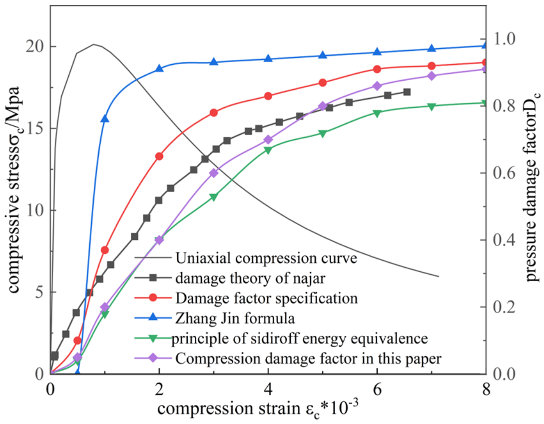


Figure2 :Comparison of compressive damage factors

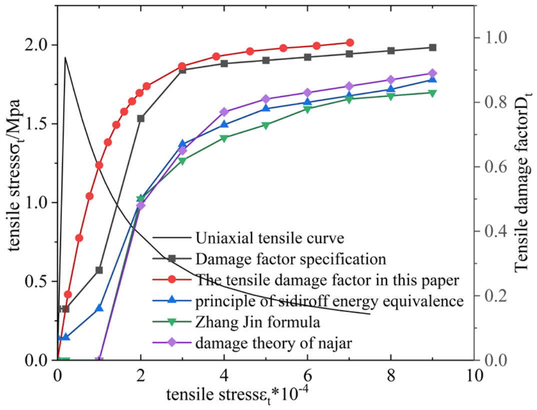


Figure3 :Comparison of tensile damage factors

It can be seen from Figs.2 and 3 that the damage factor calculated by the standard damage evolution parameters and the Sidiroff energy equivalence principle still has damage when the tensile stress is 0, which indicates that its accuracy needs to be further improved. Relatively speaking, the tension formula may be on the high side when calculating the compression damage factor, while it may be on the low side when calculating the tensile damage factor, so the overall accuracy is also low. The damage factor of Najar damage theory has higher accuracy than other models. In the absence of data support, Najar damage theory can be considered to calculate the damage factor. In this paper, the Najar damage theory is used to derive the relationship between the damage evolution parameters and the damage factor [18]. The curve of the damage factor is more accurate, and the expression is as follows:

$$d = 1-\left(1-D_t\right)^2 \frac{E_0}{E_r} \tag{1}$$

$$D_t = \begin{cases} 1-\left[\rho_t\left(1.2-0.2x^5\right)\right]^2 \dfrac{E_0}{E_r}, (x \le 1) \\ 1-\left[\dfrac{\rho_t}{\alpha_t\left(x-1\right)^{1.7}+x}\right]^2 \dfrac{E_0}{E_r}, (x>1) \end{cases} \tag{2}$$

$$x = \frac{\varepsilon}{\varepsilon_{t,r}} \tag{2}$$

$$\rho_t = \frac{f_{t,r}}{E_0 \varepsilon_{t,r}} \tag{3}$$

ISSN 2663-1563 Vol. 7, Issue 1: 77-87, DOI: 10.25236/AJAGE.2025.070110

$$D_c = \begin{cases} 1-\left(\dfrac{n\rho_c}{n-1+x^n}\right)^2 \dfrac{E_0}{E_r}, (x \le 1) \\ 1-\left[\dfrac{\rho_c}{\alpha_c (x-1)^2 + x}\right]^2 \dfrac{E_0}{E_r}, (x>1) \end{cases} \tag{4}$$

$$x = \frac{\varepsilon}{\varepsilon_{c,r}} \tag{5}$$

$$n = \frac{E_0 \varepsilon_{c,r}}{E_0 \varepsilon_{c,r} - f_{c,r}} \tag{6}$$

$$\rho_c = \frac{f_{c,r}}{E_0 \varepsilon_{c,r}} \tag{7}$$

In the formula, ac and at are the parameters of the descending section of the uniaxial compression and tensile stress-strain curves of concrete ; fc, ft are the representative values of uniaxial compressive strength and tensile strength of concrete ; e, r and uniaxial compressive and tensile strength represent the corresponding peak tensile strain of concrete ; dc, dt are the damage evolution parameters of concrete under uniaxial compression and tension ; er is the elastic modulus of concrete after unloading and loading in the elastic state.

3.2 Pile-soil interaction

Since the simulation results of the pile-soil interface have an important impact on the project, in order to more fully reflect the interaction between the pile and the soil, a surface contact model is used between the pile side and the soil. The pile side surface is regarded as the main contact surface, while the pile side soil surface is the secondary contact surface. The contact properties are mainly defined by the normal behavior model and the tangential behavior model. The tangential behavior defines the friction coefficient of the contact surface by the penalty friction formula, and the normal behavior adopts the ' hard contact ' method.

3.3 Establishment of the model

The pile foundation of this model adopts the concrete plastic damage model, in which the soil uses the Mohr-Coulomb model. Because the pile foundation will be affected by the soil boundary, the width of the model is set to 40 m and the height is set to 60 m. The material parameters of the whole model are shown in Table 2. In this paper, the pile is regarded as an ideal elastic material. Considering the geometric nonlinearity, the soil and the pile are divided into eight-node hexahedral and four-node tetrahedral grids. By properly encrypting the pile foundation and its closely adjacent soil grids, the efficiency of the calculation and the accuracy of the results are ensured.

Table 2:Finite element analysis model material parameters

name of the material	Elastic modulus E / MPa	poisson ratio *N*	Forceof cohesion c/kpa	angle of friction φ/(。)	gravity ϒ /(KN/m³)
pile foundation	3.0 ×10⁴	0.2	—	—	25.0
soil	40	0.3	15	20	14
Stripping 6.0 cm	2.4 ×10⁴	0.2	—	—	25
Peeling off 9.0 cm	2.3 ×10⁴	0.2	—	—	25
Peeling off 12cm	2.1 ×10⁴	0.2	—	—	25
Peeling off 15cm	1.8 ×10⁴	0.2	—	—	25

ISSN 2663-1563 Vol. 7, Issue 1: 77-87, DOI: 10.25236/AJAGE.2025.070110

The size of the pile group foundation is shown in Figure 4, using C30 concrete, in which the pile diameter of the single pile is 1 m, the pile length is 30 m, the size of the cap is set to 9m × 9m, and the thickness is 1.5m.There are 9 piles under the cap. The pile group foundation and the soil model network are shown in Figure 5 and Figure 6. In the finite element model, the parameters of the cap and the pile are consistent. Since each pile is connected to the pile cap during construction, the pile cap and the pile are regarded as a whole during modeling.

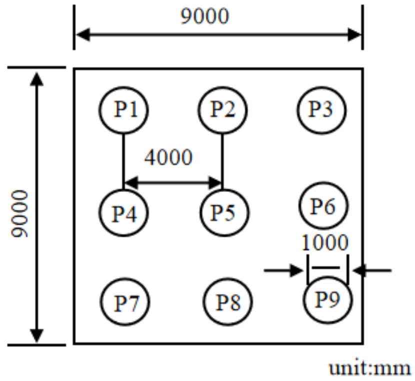
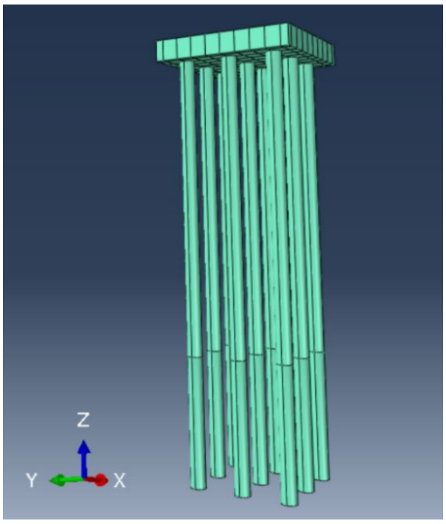


Figure 4 :Pile group layout plan



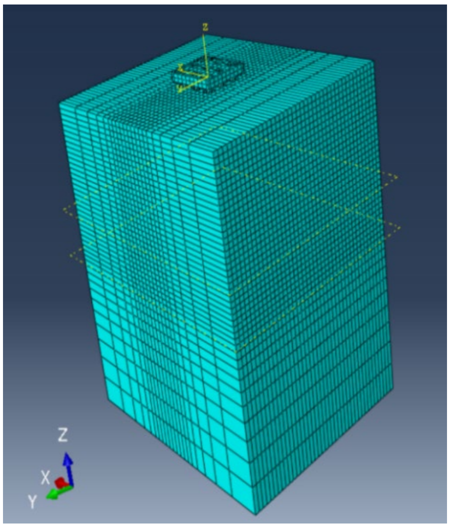


Figure 5 :Pile-cap model

Figure 6 :Overall grid division of pile group and soil

3.4 Process analysis

The spalling of concrete is expressed by the change of elastic modulus. In the simulation analysis, the influence of the attenuation of elastic modulus on the corrosion of pile foundation is mainly considered. The static elastic modulus of concrete will decrease after corrosion. Based on the measured static elastic modulus in Reference [19], the damage of concrete after corrosion was simulated. Therefore, in the numerical simulation, the elastic modulus of the pile foundation material is set to 80%, 75 %, 70 % and 60 % of the original value, respectively.

4. Finite element calculation results and analysis

4.1 Determination of ultimate bearing capacity of pile group before corrosion

The load-settlement curve of single pile before corrosion is shown in Fig.7. The Q-S curve of the pile foundation is a slow deformation curve, and there is no obvious steep drop section. According to the Technical Code for Detection of Building Foundation Piles (JGJ 106-2014) [20], for this kind of slow deformation Q-S curve, the load value corresponding to 40 mm settlement can be used as the ultimate load of pile foundation. The ultimate load is 5124.5kN, and half of its ultimate load is taken as the working load.

ISSN 2663-1563 Vol. 7, Issue 1: 77-87, DOI: 10.25236/AJAGE.2025.070110

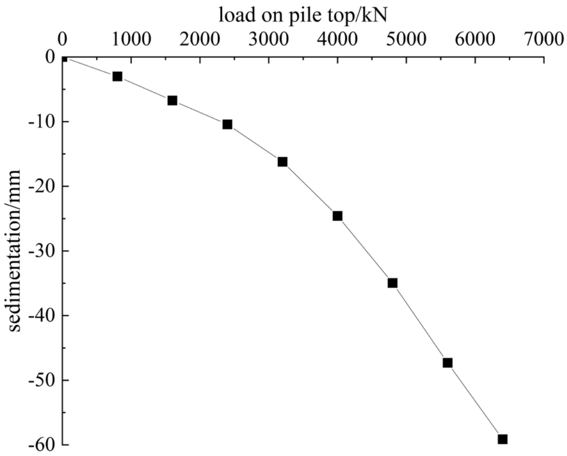


Figure 7:Single pile load-settlement curve

Because the load transfer of pile group is different from that of single pile, although there are various empirical formulas at present, more in-depth research is needed. The Technical Code for Building Pile Foundations (JGJ94-2008) [21] mentions that the pile top effect of pile group foundation can be calculated by relevant formulas. Without considering the pile group effect, the vertical ultimate bearing capacity of pile group can be simplified to the sum of the vertical compressive bearing capacity of each single pile. In this chapter, the ultimate bearing capacity of single pile when the settlement reaches 40 mm is taken as the reference value, and the ultimate bearing capacity of single pile is multiplied by the number of pile groups n as the ultimate bearing capacity of pile group system. This method not only simplifies the calculation process of pile group bearing capacity, but also ensures the stable convergence of the finite element model in the calculation process. The Q-S curve of the pile is shown in Figure 8.

$$N_k = \frac{F_k + G_k}{n} \tag{8}$$

In the formula, F is the vertical force acting on the top surface of the cap under the standard combination of load effect ; n is the average vertical force of the pile ; g is the self-weight stress of pile cap and soil on pile cap ; n is the number of piles of pile foundation.

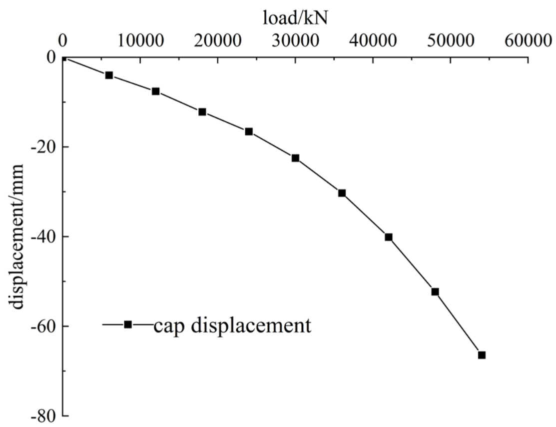


Figure 8:Pile group load-settlement curve

4.2 Analysis of bearing capacity of pile foundation after corrosion damage

The curve of the displacement of the pile cap and each pile as a whole with the vertical load and the relationship between the ultimate bearing capacity and the spalling thickness are shown in figure 9. From the diagram, it can be concluded that with the deepening of the corrosion degree of the bridge pile foundation, which means the increase of the peeling thickness, the displacement of the pile top also increases under the same vertical load. When the load reaches 30000 kN, the displacement of the pile top begins to increase obviously. When the vertical load is stable at 41530 kN, with the increase of the degree of corrosion, the settlement also increases from 40 mm to 45.53 mm, showing a significant positive

ISSN 2663-1563 Vol. 7, Issue 1: 77-87, DOI: 10.25236/AJAGE.2025.070110

correlation.

From condition I to condition IV, with the increase of peeling thickness, the ultimate bearing capacity of pile foundation decreases gradually. The ultimate bearing capacity of pile foundation without corrosion is 41530 kN. When the peeling thickness is 6cm, 9cm, 12cm and 15cm, the ultimate bearing capacity decreases from 41530 kN to 40958 kN, 40454 kN, 39642 kN and 39299 kN respectively. Compared with before corrosion, the vertical bearing capacity decreased by 1.3 %, 2.5 %, 4.5 % and 5.4 % respectively. It shows that the vertical ultimate bearing capacity of pile group pile foundation decreases with the increase of corrosion degree.

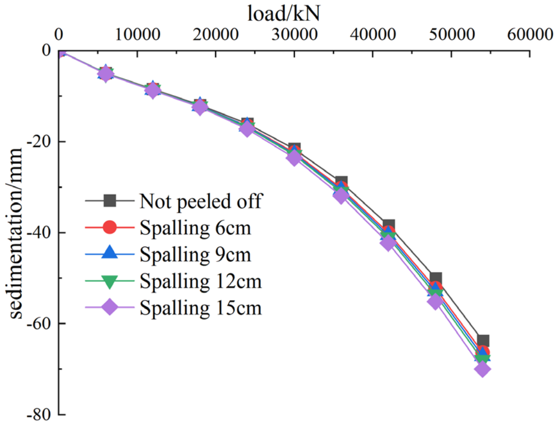
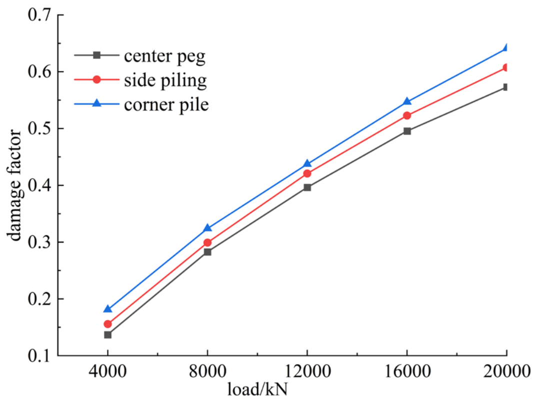
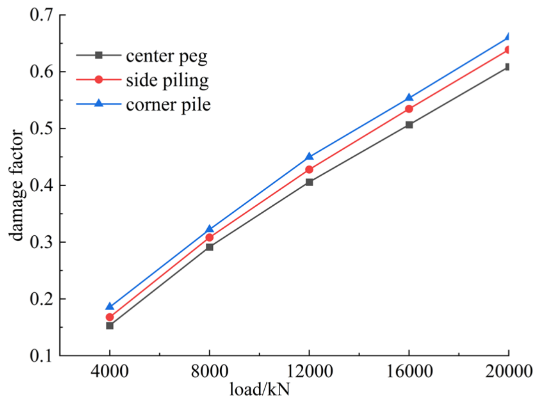


Figure 9 :Load-displacement curves of pile groups under different spalling thicknesses

With the increase of service life and repeated load, the bearing capacity of corroded pile foundation will be significantly reduced, because the formed corrosion products and cracks will further accelerate the corrosion process, and the loose structure produced by corrosion will adsorb more corrosive media, forming a vicious circle. From the pile top damage factor in Fig.10, it can be seen that the damage factors used to indicate the degree of damage are also different under different peeling thicknesses. As the load continues to increase, until the load is loaded to the working load, the damage degree of the corner pile is greater than that of the side pile, and the side pile is greater than the center pile. When the peeling thickness increases, the damage factor gap between the corner pile, the side pile and the center pile decreases, and the damage factor of the center pile increases significantly, because the load ratio of the center pile increases. Due to the combined effects of factors such as decreased bearing capacity and accelerated corrosion, the service life of bridge pile foundations will be greatly shortened.



(a) d=6.0cm



(b) d=9.0cm

ISSN 2663-1563 Vol. 7, Issue 1: 77-87, DOI: 10.25236/AJAGE.2025.070110

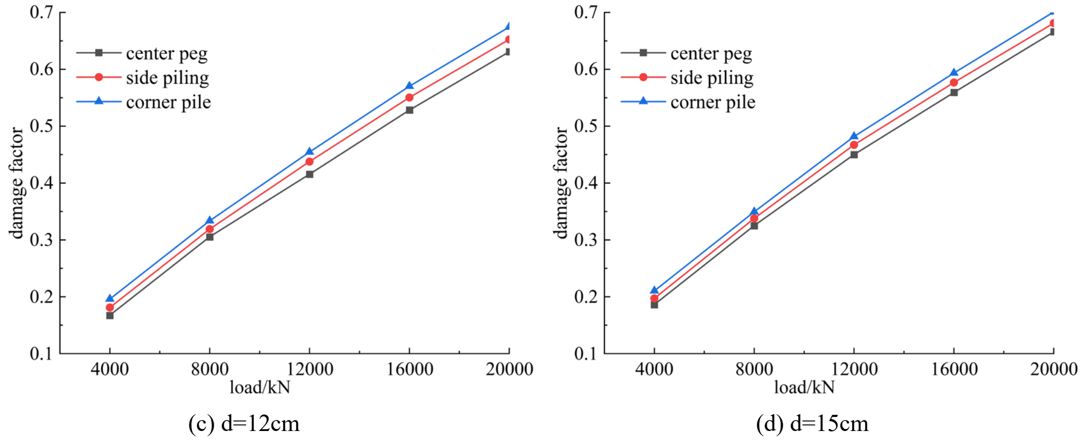


Figure 10 :The damage change of pile top with the increase of load under different peeling thickness

Fig.11 shows that in the axial force diagram of pile body under different corrosion degrees under working load, the axial force value of pile body shows the trend of corner pile > side pile > middle pile. With the increase of the peeling thickness, the axial force of the central pile and the side pile is gradually close to the axial force of the corner pile. When the peeling thickness reaches 15 cm, the axial force values of the three are close to each other.

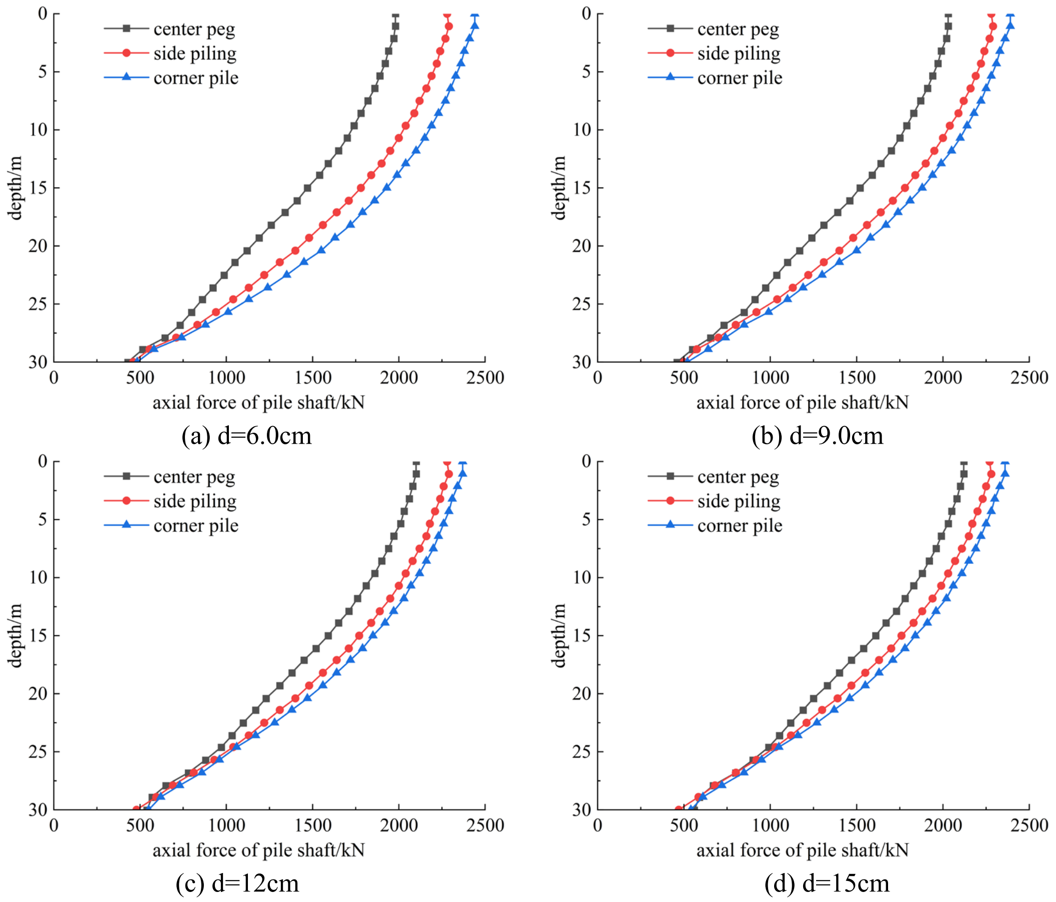


Figure11 :Axial force of pile with different corrosion degree under working load

As shown in Fig.12, when the degree of corrosion is small, the order of pile side friction is : middle pile < side pile < corner pile. With the increase of concrete spalling thickness, the friction resistance of the three is gradually close. The friction resistance of the lower half of the corner pile gradually decreases with the increase of the degree of corrosion, indicating that with the increase of the degree of corrosion, the side friction resistance of the middle pile and the lower part of the side pile plays a more obvious role.

ISSN 2663-1563 Vol. 7, Issue 1: 77-87, DOI: 10.25236/AJAGE.2025.070110

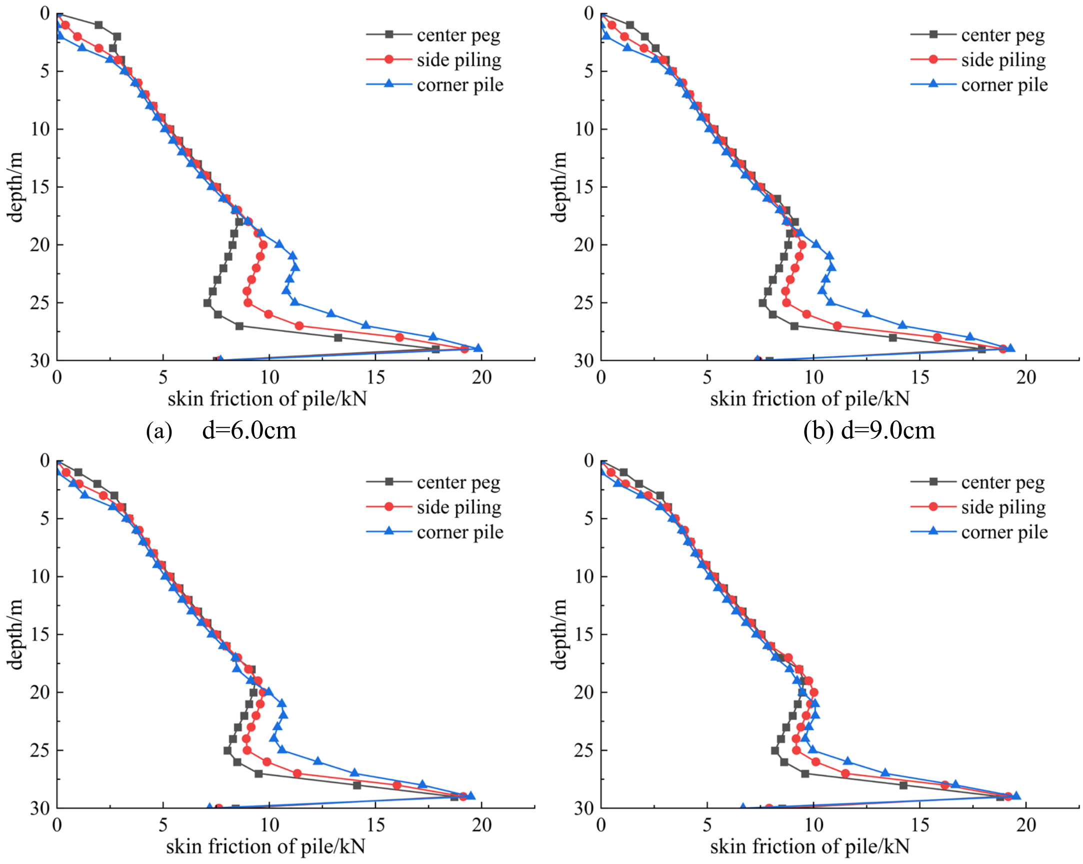


Figure12 :Pile side friction resistance of different corrosion degree under working load

Fig.13 shows the load sharing ratio of foundation piles under working load. With the increase of corrosion degree, the load sharing ratio of corner piles decreases gradually, while that of side piles increases slowly, while that of middle piles increases rapidly. This shows that under the action of working load, the force of the upper load mainly acts on the corner pile at the beginning. With the deepening of the corrosion degree, the load gradually transfers to the side pile and the middle pile, especially the bearing proportion of the middle pile increases obviously. Under the condition of ultimate load, as shown in Fig.14, when the upper load is large, the load sharing of the initial corner pile, the side pile and the middle pile is similar. With the increase of corrosion degree, the side pile and the middle pile gradually bear more load, while the load sharing ratio of the corner pile decreases slowly. This shows that when the corrosion degree is serious, the load sharing effect of the side pile and the middle pile is enhanced. Therefore, the analysis of the bearing capacity of the side pile and the middle pile should be paid attention to in the actual engineering design.

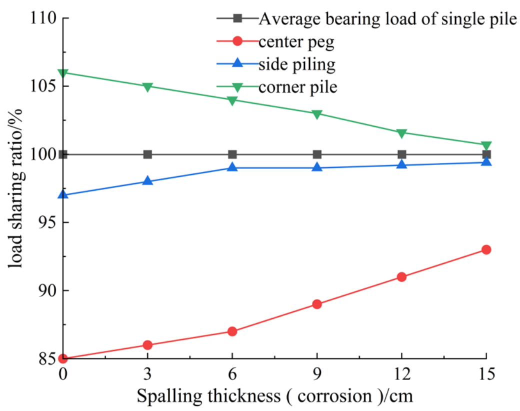


Figure 13 :Pile load sharing ratio under working load

ISSN 2663-1563 Vol. 7, Issue 1: 77-87, DOI: 10.25236/AJAGE.2025.070110

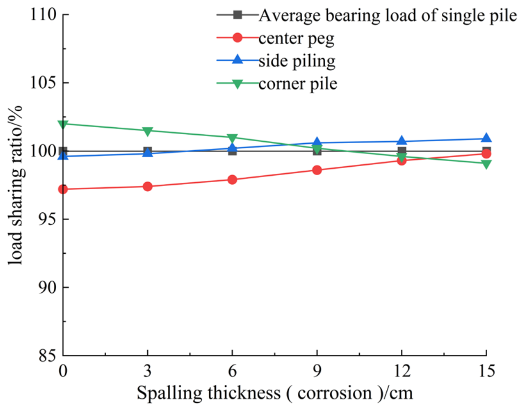


Figure 14 :Pile load sharing ratio under ultimate load

5. Conclusion

Through the analysis and calculation of finite element software, the variation trend of vertical bearing capacity of pile group before and after corrosion and some characteristics of pile foundation damage caused by corrosion are studied. The main conclusions are as follows :

(1) When analyzing the damage of pile foundation, using Najar damage theory to derive the calculation formula of damage evolution parameters and damage factors in the code has sufficient theoretical basis and high precision, and can better describe the damage process of CDP model under load.

(2) After the corrosion of the pile foundation, with the deepening of the corrosion degree, the vertical ultimate bearing capacity of the pile group pile foundation shows a downward trend, while the vertical displacement of the pile foundation is an upward trend.

(3) Under the working load, with the increase of service time and repeated load, the damage degree of corroded bridge is increasing. The axial force value and damage degree of pile body are shown as corner pile > side pile > middle pile. With the deepening of corrosion degree, the load gradually turns to side pile and middle pile, and the sharing ratio of middle pile increases significantly.

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