

Influence of Grouting Interruption on Mechanical Performance of Offshore Wind Turbine Jacket Foundation Connection

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Abstract. Offshore working environment is complex and variable, and sometimes the grouting pipe is blocked and cannot be continued in the offshore wind power jacket foundation. In this paper, the effect of grouting interruption on the mechanical performance of jacket foundation connection was analyzed by numerical simulation. Firstly, a finite element analysis model for the axial force behavior of grouting connection was established, and the validity was verified by existing experiments. Then three different simulation methods of grouting interruption were compared and analyzed. Moreover, the parameters of grouting break position, shear key height, shear key spacing, the thickness of grouting body and the number of shear key were analyzed. Based on the analysis results, a calculation method of bearing capacity for rapid assessment of the grouting interruption was established.

Keywords: Offshore wind power, jacket foundation, grouting connection, grouting pipe plugging, carrying capacity, FEA.

1. Introduction

With the proposed dual-carbon goal, the development of renewable energy has become a national energy strategy, and offshore wind power is an important strategic support for China's energy structure transformation [1]. Among common offshore wind power foundations, jacket foundations have a wide range of water depths and significant economic benefits, and are widely used [2]. The pipe jacket and the pipe pile are usually connected by grouting technology, which pumps high-strength and fast-hardening cement-based grouting materials in the annular space between the pipe pile and the jacket [3]. However, due to the complex and changeable environment of offshore operation, it is often impossible to continue construction due to the blockage of grouting pipes. In order to prevent pipe blockage resulting in construction difficulties, a spare grouting pipelines are usually designed in advance in the project. Even so, backup grout lines can still be blocked. After the grout has been interrupted for a period of time, the hardened grout surface cannot be treated when the grout is re-grouting, and floating slurry or sediment will cause the old and new grout to be unable to fully integrate into a whole.

In this paper, the effect of grouting interruption on the mechanical performance of jacket foundation connection was analyzed by numerical simulation. Firstly, a finite element analysis model for the axial force behavior of grouting connection was established, and the validity was verified by existing experiments. Then three different simulation methods of grouting interruption were compared and analyzed. Moreover, the parameters of grouting break position, shear key height, shear key spacing, the thickness of grouting body and the number of shear key were analyzed. Based on the analysis results, a calculation method of bearing capacity for rapid assessment of the grouting interruption was established.

2. Establishment and Validity of Finite Element Model

2.1. Establishment of Finite Element Model

The commercial finite element software ABAQUS was used to analyze axial bearing performance of grout connections. According to the symmetry of the geometry and loading mode with respect to the axis of the inner and outer steel tubes (Fig. 1a), an axisymmetric model was applied to improve the analysis efficiency. The steel pipes and grout in the specimen were simulated by a 4-node quadrilateral axisymmetric element (CAX4I). The element is a incompatible mode element, which can effectively overcome the shear self-locking problem, and is also suitable for the model of contact problems.

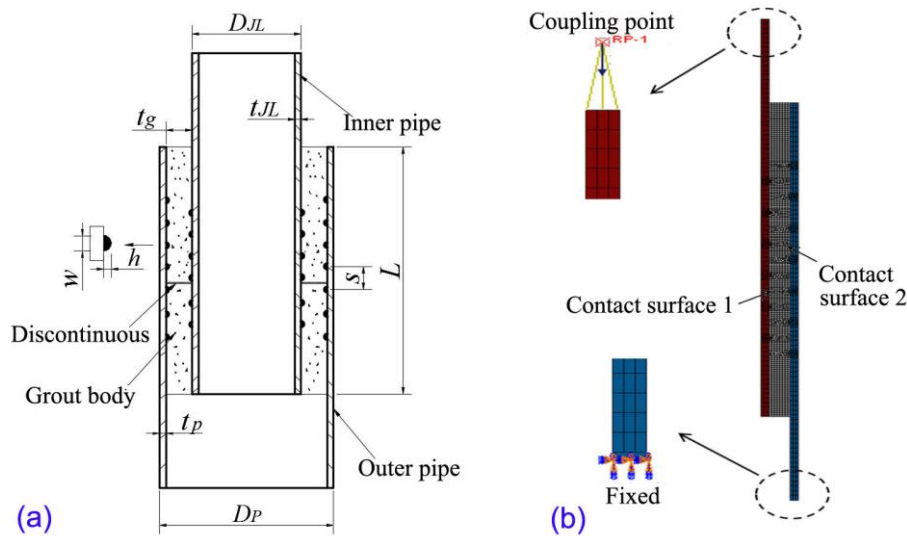


Figure 1. Configuration and finite element model of grouting connection: (a) Configuration; (b) finite element model

A bi-linear kinematic hardening elastic-plastic material model was adopted for steel, and in which von Mises yield criterion was adopted. The tangential modulus of the strengthening stage E_t is equal to $0.01E_s$, and E_t was the elastic modulus of steel. The concrete damage plastic model was used to simulate the material damage and stiffness degradation properties of the grout body. The uniaxial stress-strain curve of concrete provided by GB50010, Code for Design of Concrete Structures, was adopted. In order to improve the convergence of calculation, the damage factor calculation method based on Sidoroff energy equivalence principle was used. Value of the calculation parameters to be entered according Table 1 when defining the plastic space of the grout material [4]. In the table, ψ is the expansion Angle, K_c is the second stress invariant, α_f is the ratio of biaxial ultimate compressive strength to uniaxial ultimate compressive strength, ε is the flow potential offset value, μ represents the viscosity coefficient, respectively.

Table 1. Calculation parameters of plastic space of grout material

$\psi/^\circ$	K_c	α_f	ε	μ
36	2/3	1.16	0.1	0.0005

The mesh size was selected by a trial calculation. The mesh of steel tubes and grout material should not be less than 3 layers in thickness direction. Due to the simplicity of the model, a more refined mesh size was adopted, and the grid after the finite elements division was shown in Fig. 1b. The displacement was applied to the top of the inner steel pipe by means of reference point coupling, and the lower end of the outer steel pipe is fixed constraint. A hard contact was used to simulate the contact between steel pipe and grout in normal direction, Coulomb friction model was adopted in tangential direction, and the friction coefficient was set to 0.4.

2.2. Validity of Finite Element Model

In order to verify the validity of the above finite element model, numerical simulations of the grouting connection tests in the literature [5-6] were carried out. Due to limitation on space, only part of the results are given here, and the specific conditions of the specimens are not detailed. Fig. 2 shows the comparison between the load-displacement curves obtained from the finite element analysis and the experimental test, from which it can be seen that the finite element analysis results in the initial stiffness, bearing capacity and deformation of the three indicators are in good agreement with the tests. Fig. 3 shows the damage pattern comparison. The damage patterns by using the finite element analysis are consistent with that by the experimental test. It can be considered that the finite element model can well simulate the performance of the grouting connection under an axial compression force.

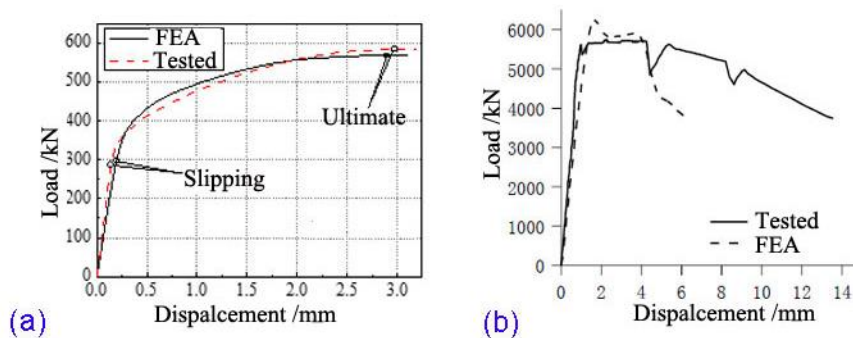


Figure 2. Comparison of finite element analysis load-displacement curves with test results: (a) the specimen W3; (b) the specimen GC-T63

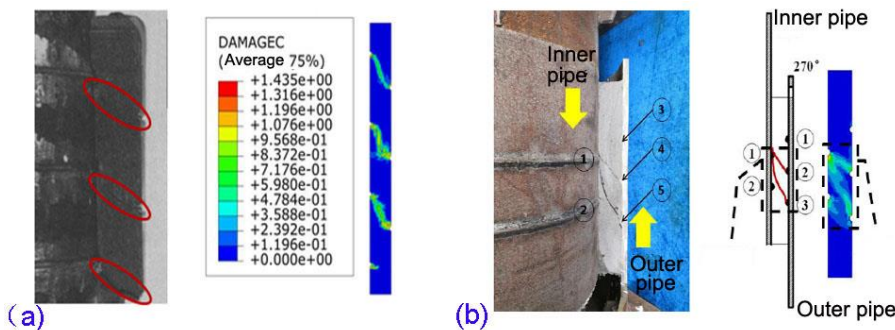


Figure 3. Comparison of finite element analysis damage modes with test results: (a) the specimen W3; (b) the specimen GC-T63

3. Simulation Methods for Interruption of Grouting Construction

Because it is not clear that the grouting process after the interruption of the mechanical properties of the location of the grout body, the following three methods to be used to simulate: Method 1, the interruption of the location of the grout body on both sides of the detachment, the two do not have contact behavior, simulation of the grouting location of the existence of more floating grout or other impurities; Method 2, the interruption of the location of the two grout body on both sides of the detachment, but there is a coulometric frictional contact between the two, simulation of the location of the grout is no floating grout and other impurities; Method 3, the grout body in the interruption position due to the existence of some floating grout strength reduction, using the interruption position $t_g/2$ range to reduce the strength of the grout body to simulate.

Using the above three methods to analyze the force performance of a project first pile method conduit frame grouting connection under axial load. The connection configuration is shown in Fig.

1a. Specific parameters are shown in Table 2. In the table, D_{IL} is the outer diameter of the inner steel pipe; t_{IL} is the thickness of the inner steel pipe; D_p is the outer diameter of the outer steel pipe; t_p is the thickness of the outer steel pipe; L is the length of the grouting; t_g is the thickness of the grouting; and h , w , and s are the height, width, and spacing of shear bonds on the wall of the steel pipe, respectively. Q345 steel was used and the nominal compressive strength of the grout body was 130 MPa.

Fig. 4 shows the curves of axial pressure versus displacement of the specimens obtained by different analytical methods. From the figure, it can be seen that the interruption of grouting reduces the peak bearing capacity of the specimen. Method 1 obtained the smallest peak bearing capacity, which was 71.5% of the intact specimen; Method 2 and Method 3 obtained peak bearing capacities of 97.6% and 93.5% of the intact specimen, respectively. Figure 5 shows the stress cloud and damage index cloud of each specimen at the maximum load. From the figure, it can be seen that the force transmission path between the grouting bodies on both sides of Method 1 was interrupted, and the adjacent upper and lower two short diagonal compression columns could not be formed; Method 2 and Method 3 interrupted parts of the grouting bodies on both sides could transmit force, and the adjacent upper and lower two short diagonal compression columns were basically formed, but Method 3 had a larger degree of damage due to the reduction of the strength of the material at the interrupted parts. In addition, it can be found from Fig. 4, grouting interruption will also reduce the stiffness of the specimen.

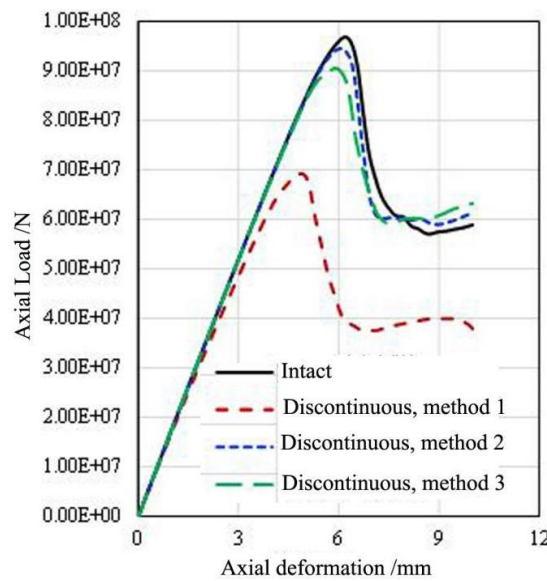


Figure 4. Comparison of load-displacement curves of different analysis methods

Table 2. Geometric parameters of grouted connections (mm)

Parameter	D_{IL}	t_{IL}	D_p	t_p	L	t_g	h	w	s
Value	1800	55	2200	55	3000	145	20	40	300

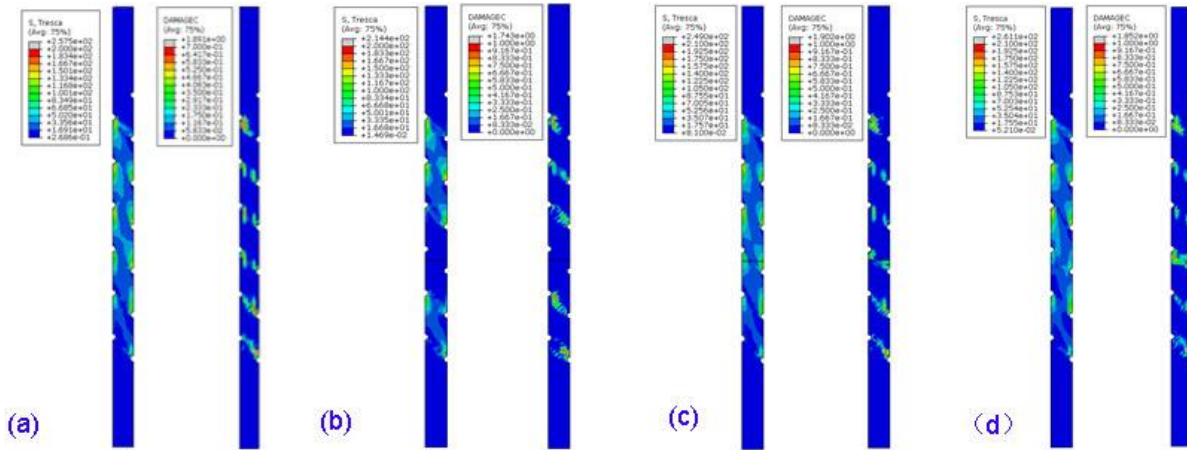


Figure 5. Comparison of stress and damage in different analysis methods: (a) intact specimen; (b) interrupted specimen-method ①; (c) interrupted specimen-method ②; (d) interrupted specimen-method ③

4. Parameter Analysis

4.1. Interruption Position

In order to understand the influence of interruption position on the load bearing performance of the connection, the interruption simulation method ③ was used to analyze the specimens with different interruption positions, and the relationship curve between the load bearing capacity and the interruption position was obtained as shown in Fig. 6. The vertical coordinate is the distance of the interruption position from the lower edge of the grouting body, and the horizontal coordinate is the ratio of the grouting interruption specimen bearing capacity P_u to the intact specimen bearing capacity P_u . It can be seen that different interruption locations have different effects on the connection bearing capacity. When the interruption location is located outside the shear bond range, the grouting interruption does not affect the bearing capacity of the connection. Macroscopically, when the interruption location is located in the middle of the connection, it has a greater impact on the load carrying capacity, which is due to the fact that two compressed diagonal columns are affected when the interruption location is in the middle, and only one is affected on the outside. Therefore, the interruption location of the grouted connection can be macroscopically categorized into three zones: the no-impact zone, the single diagonal compression column impact zone, and the double diagonal compression column impact zone. In addition, the relative position of the interruption and the shear key will also affect the bearing capacity, the interruption is located in the inner pipe shear key has the smallest impact, and is located in the middle of the inner pipe shear key and the outer pipe shear key has the largest impact.

4.2. Height of Shear Keys

Fig. 7a is a comparison of the relation curves between the connection bearing capacity and the break position when the shear key heights are 10mm, 15mm and 20mm respectively. The three specimens are the same except for the different shear key heights. It can be seen from the figure that the higher the shear key, the greater the influence of grouting interruption on its influence. There are two failure modes of grouting connection under axial pressure: slip and shear failure of grouting barodiagonal column. The smaller the shear bond height is, it tends to slip failure, and the stress is not uniform respectively. There is a stress concentration near the outermost shear bond, but the grouting interruption will make the stress tend to be uniform, and the bearing capacity will increase instead of decreasing. When the shear key height is large, the grouting body is destroyed in the form of baroclinic column, and the grouting body is the same in each baroclinic column. The grouting interruption makes the adjacent baroclinic column cannot be formed, resulting in the decrease of

bearing capacity. The damage stress cloud diagram of intact specimen under peak load is shown in Fig. 7b.

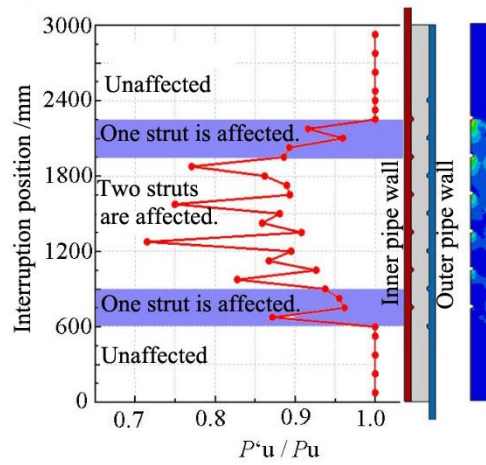


Figure 6. Influence of interrupt position on the bearing capacity

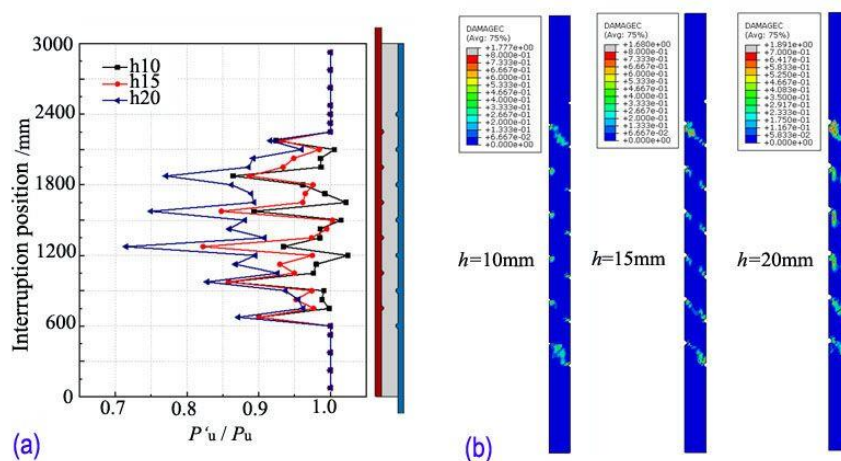


Figure 7. Comparison of the heights of different shear keys: (a) Bearing capacity-grouting break position relationship curve; (b) grout damage map

4.3. Shear Key Spacing

Fig. 8a is a comparison of the relation curves between the connection bearing capacity and the break position when the shear key spacing is 200mm, 300mm and 400mm, respectively. It can be seen that when the shear key spacing is 300mm, the grouting interruption has the most obvious influence on the connection bearing capacity. Fig. 8b shows the grout damage cloud image under peak load of three specimens in good condition. Specimens with shear bond spacing of 30mm have larger and more uniform damage area than those with shear bond spacing of 400mm. The specimen with shear bond spacing of 200mm has a larger damage area, and a short diagonal column is formed across the shear bond in the lower area. When the shear bond is interrupted in this area, the bearing capacity decreases obviously. The reduction of bearing capacity in other areas is less than that of specimens with shear key spacing of 300mm.

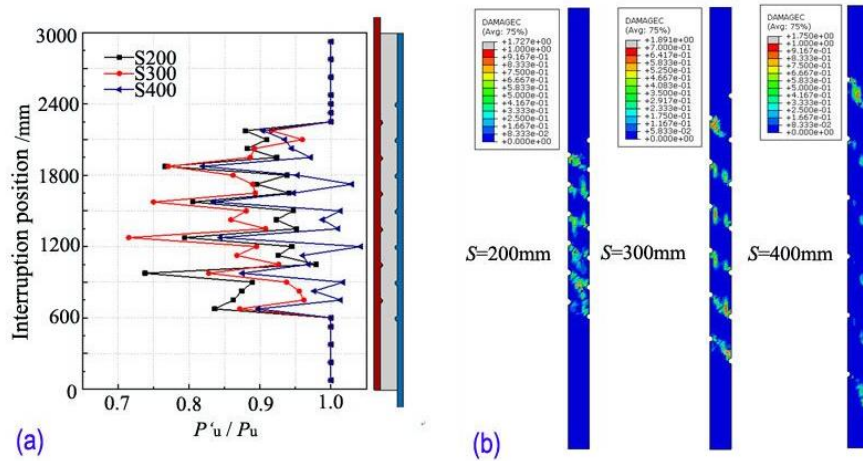


Figure 8. Comparison of different shear key spacing: (a) bearing capacity-grout interruption location relationship curve; (b) grout body damage cloud

4.4. Thickness of Grout Body

Fig. 9 shows the comparison when the thickness of grout body is 85mm, 105mm and 145mm, respectively, in which Figure 9a is the comparison of the relationship curve between the connection bearing capacity and the interruption position, and Fig. 9b is the grout body damage cloud diagram. It can be seen that the grout body damage of the three specimens is generally similar, and the impact of grout interruption on the bearing capacity of the three specimens is basically the same.

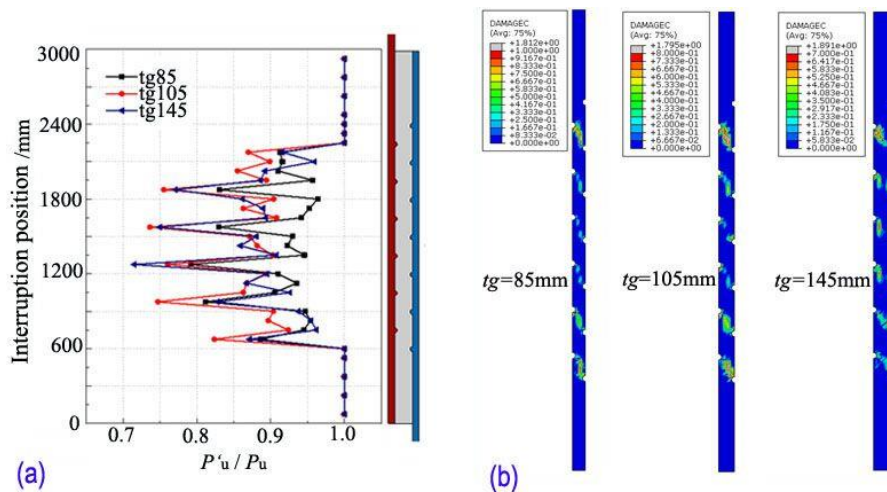


Figure 9. Comparison of different grout body thicknesses: (a) bearing capacity-grout interruption position relationship curve; (b) grout body damage map

4.5. Number of Shear Keys

Fig. 10 shows a comparison of the load carrying capacity-grout interruption location relationship curves for the specimens with the number of shear keys of 4, 6 and 8, respectively. From the figure, it can be seen that as the number of shear keys increases, the degree of influence of grout interruption on the load carrying capacity of the connection decreases.

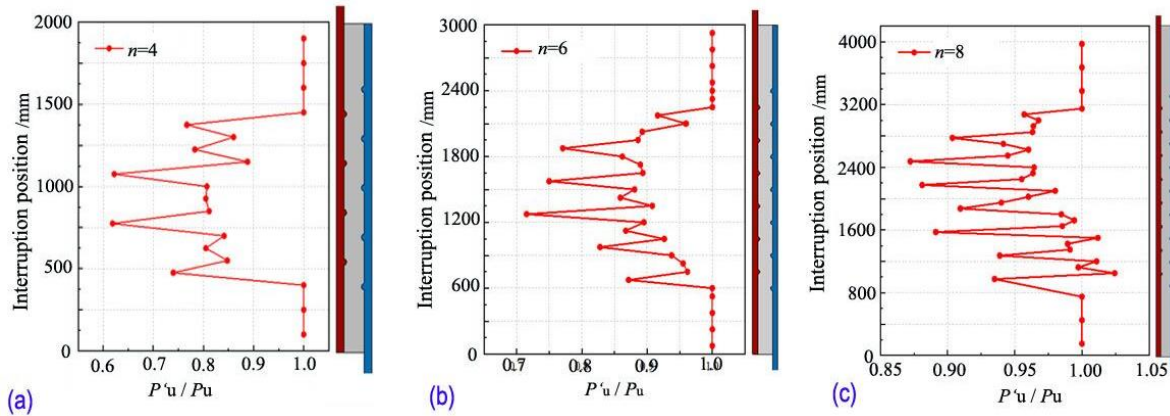


Figure 10. Comparison of bearing capacity-grout interruption position relationship curves for specimens with different number of shear keys: (a) $n = 4$; (b) $n = 6$; (c) $n = 8$

5. Method of Rapid Evaluation of Load Carrying Capacity

From the above analysis, it can be seen that the number of shear keys is the key factor affecting the reduction of the load carrying capacity of the connection. The number of effective shear keys is reduced due to the failure of adjacent shear keys caused by the interruption of grouting. For single inclined column influenced zone and double inclined column influenced zone, the number of failed shear keys can be considered as 1 and 2 respectively. Therefore, the reduction of bearing capacity due to grouting interruption can be calculated according to equation (1).

$$\frac{P'_u}{P_u} = \frac{n_e}{n} \tag{1}$$

Where n_e is the number of effective shear keys. The interruption location is in the single oblique column influence area when $n_e = n - 1$; interruption location is in the double oblique column influence area when $n_e = n - 2$.

Fig. 11 shows the comparison between the calculated connection bearing capacity according to equation (1) and the finite element results. From the figure, it can be seen that the theoretical results are in good agreement with the numerical results for the influence zone of monoclinic columns; due to the connection shear key height, shear key spacing, grout thickness and so on have some influence on the load carrying performance, the theoretical results for the influence zone of double inclined columns are slightly lower compared with the numerical results, and it can be considered that Eq. (1) has a certain degree of reliability.

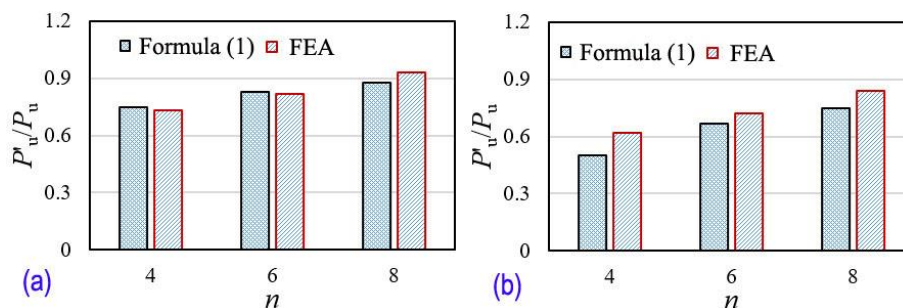


Figure 11. Comparison between the theory of load carrying capacity of the connection considering the influence of interruptions and the finite element results: (a) zone of influence of a single inclined column; (b) zone of influence of a double inclined column

6. Conclusions

Grouting interruptions may reduce the axial bearing capacity of grouted connections in offshore wind power foundations. The grouting connection can be divided into three zones according to whether there is an impact and the magnitude of the impact: no impact zone, monoclinic column impact zone, and biclinic column impact zone. When the grouting interruption is in the no-impact zone, it has no effect on the connection bearing capacity; when it is in the monoclinic column-impact zone and the biclinic column-impact zone, the connection bearing capacity can be quickly estimated according to equation (1).

The method of grout body detachment on both sides is used to simulate the impact caused by grout body interruption is lower than the bearing capacity obtained by the other two methods, and it can be considered as a safer way to consider the impact of grout interruption, and the results of the bearing capacity obtained are the lower limit.

The lack of experimental data on the mechanical properties of the grout body at the grout interruption requires further research.

Acknowledgments

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