Effect of honeycomb bulkheads on uniaxial undrained bearing capacities of wide-shallow bucket foundation

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Abstract. In order to study the effect of honeycomb bulkheads on uniaxial undrained bearing capacities of wide-shallow bucket foundation, the finite element models of bucket foundations with and without bulkheads on soft ground were established respectively. A large number of 3D finite element analyses have been performed to obtain uniaxial bearing capacities of the two foundations with different embedment ratios and soil shear strength heterogeneity by using displacement control method. The results show that, for homogenous clay, all the vertical, horizontal and moment bearing capacities of the wide-shallow bucket foundation are not affected by the honeycomb bulkheads. For non-homogenous clay, the moment bearing capacity of the wide-shallow bucket foundation is obviously affected by the honeycomb bulkheads, while the effect for improving the vertical and horizontal bearing capacity of the bucket foundation can be neglected. For the convenience of designers reference, simplified calculation equations for undrained bearing capacities are fitted according to the finite element results.

1. Introduction

As the basis of offshore wind power equipment, besides the vertical loads from the upper structure, the offshore wind foundation needs to further withstand the huge horizontal loads and bending moments caused by wind, waves and current loads. Its safety and stability can directly affect the power generation capacity and efficiency. According to design code (Offshore Standard DNV-OS-J101, 2014), the tolerance of the total rotation at seabed is 0.5°. In China, according to the provisions of the design code (FD003-2007), when the wind turbine with hub heights exceeds 100m, the angular rotation of the foundation is less than 0.17° (3‰ for levelness) and the settlement is less than 100mm. Therefore, different from the ocean engineering of oil platform and breakwater, etc., higher requirements are put forward for both design and construction of the offshore wind foundation.

Thirteen offshore wind foundations are adopted with a new type wide-shallow bucket foundation-composite bucket foundation in Dafeng wind power farm of China. The foundation is consists of three parts from top to bottom: the concrete transition segment and beam-slab structure, and the lower thin-walled steel bucket, as shown in Figure 1. This foundation is different from the traditional narrow-deep bucket foundation for its super-large diameter and shallow embedment depth, aiming to exert its advantage of withstanding horizontal and moment loads, and effectively control the deformation of the
foundation[1]. In addition, composite bucket foundation makes one-step installation possible, which greatly shortens construction period, and reduces construction cost and difficulty.

In order to investigate the bearing capacity of the bucket foundation, scholars have made a great amount of experimental research [2–4] and numerical simulation [5–7]. However, the research object is mainly the bucket foundation without bulkheads. For controlling the stability of composite bucket foundation during towing and negative pressure sinking process in practice, the steel bucket is divided into seven compartments by honeycomb bulkheads, as shown in Figure 2. The bearing capacity of bucket foundation can be improved under some conditions by way of setting bulkheads. Le et al. [8] quantitatively compared the bearing capacity of concrete bucket foundations with and without honeycomb bulkheads by finite element method. The results show that the bulkheads can effectively improve anti-sliding and anti-overturning ability of foundation. Lian et al. [9] have shown through experiments that, with the bulkheads, the ultimate bearing capacity of the bucket foundation under horizontal and moment loading is increased by 20.2%. The bearing capacity of bucket foundation in undrained clay is fundamentally important in geotechnical engineering[10–12]. However, there has no researches relating to the effect of honeycomb bulkheads on the undrained bearing capacity of wide-shallow bucket foundation been carried out at home and abroad.

![Figure 1. Pictures of composite bucket foundation.](image1)

![Figure 2. Internal honeycomb bulkheads.](image2)

In this study, the finite element models of bucket foundations with and without honeycomb bulkheads were established. With these models, the effect of honeycomb bulkheads on the bearing capacity of the wide-shallow bucket foundations under different embedment ratios and soil shear strength heterogeneity was analyzed. Moreover, the simplified equations for calculating the uniaxial bearing capacities of the foundation were also obtained.

2. Numerical Simulation

2.1 Model geometry, mesh and material parameters

Since the main research object of this study is the steel bucket foundation, neither the transition segment nor the beam-slab structure was taken into consideration for the finite element modeling. Instead, the finite element models for steel bucket foundation with and without honeycomb bulkheads were established respectively, see Figure 3. The bucket foundation embedment ratio $L/D$ was defined as 0.1, 0.2, 0.3, 0.4, 0.5, where $D$ is the diameter of the bucket foundation and $L$ is the skirt length. By taking the actual dimension of 3.3MW offshore wind foundation in Dafeng wind power farm for references, the value of $D$ was set as 30m, steel plate thickness of the bucket wall was set as 25mm, and steel plate thickness of the bulkheads was set as 15mm. An eight-node liner hybrid solid element was used to model the soil, the diameter and depth of soft ground were set as $8D$ and $8L$ respectively.
In this study, the central point of the foundation bottom was set to the reference point (RP), and assuming that all the loads act on this point, as shown in Figure 4. In addition, the finite element results show that the loading direction angle has little impact on the uniaxial bearing capacities of the bucket foundation with honeycomb bulkheads, therefore, the direction parallel to the bulkheads was taken as the horizontal loading direction.

The ideal elastoplastic constitutive model based on the Tresca yield criterion was adopted for numerical simulation of soil. As shown in Figure 4, the undrained shear strength of the soil at the mud surface was set as $s_{um}$, the increasing rate of undrained shear strength with depth $z$ is $k$, the undrained shear strength of the clay can be obtained according to Equation (1):

$$s_u = s_{um} + kz$$

(1)

In order to obtain the dimensionless quantity of the soil shear strength, the soil shear strength heterogeneity index $\kappa$ was introduced in, as shown in Equation (2):

$$\kappa = \frac{kD}{s_{um}}$$

(2)

In this study, the value of $\kappa$ was set as 0, 1, 3, 6, 12, and 30, where $\kappa=0$ indicates that the soft ground is homogeneous soil. Moreover, the elastic modulus $E=500s_u$, Poisson's ratio $\nu=0.499$, and effective gravity $\gamma'=6\text{KN/m}^3$.

The interface between the bucket foundation and soil was assumed to be fully rough, that is no separation permitted [2, 4, 12].

2.2 Loading methods, Sign convention and notation

The displacement control method was adopted for applied load onto the bucket foundation. The tangent intersection method was used to obtain the ultimate bearing capacity under uniaxial loading.

In this study, the sign convention were adopted from Butterfield et al. [13]. Table 1 indicates the notation for loads and displacements.

| Vertical | Horizontal | Rotational |
|----------|------------|------------|
| Displacement | $\omega$ | $u$ | $\theta$ |
| Load | $V$ | $H$ | $M$ |
| Uniaxial capacity | $V_{ult}$ | $H_{ult}$ | $M_{ult}$ |
| Bearing capacity factor | $N_{CV} = V_{ult}/A_{s0}$ | $N_{CH} = H_{ult}/A_{s0}$ | $N_{CM} = M_{ult}/AD_{s0}$ |

Note: $s_{0}$ is undrained shear strength at depth $D/4$ below skirt tip level.

2.3 Validation

Table 2 shows the comparison between the finite element results and the results of the skirted strip foundation in non-homogenous clay in Yun et al. [14] research. The results show that the maximum
vertical bearing capacity error is 6.27%. Table 3 shows that the error of the finite element results and the horizontal bearing capacity of Coffman et al. [15] model test is controlled within 5%. The above comparisons show that the undrained bearing capacity of bucket foundation determined from finite element analyses is reliable.

| L/D | Vult (KN) | Error(%) |
|-----|-----------|----------|
| 0.2 | 6689.24   | 7108.94  | 6.27 |
| 0.5 | 14323.49  | 14830.90 | 3.54 |
| 1.0 | 25980.47  | 27130.70 | 4.43 |

| Bucket embedded depth (m) | Depth to loading point (m) | Hult (KN) | Error(%) |
|---------------------------|----------------------------|-----------|----------|
| 0.813                     | 0.660                      | 0.290     | 0.283    | 2.41 |
| 0.805                     | 0.381                      | 0.196     | 0.187    | 4.60 |
| 0.820                     | 0.610                      | 0.345     | 0.328    | 4.93 |

3. Evaluation of uniaxial undrained bearing capacities

3.1 Bearing capacity factors and Simplified calculation formulas

In this study, the effect of embedment depth and non-homogeneity of clay on bearing capacity factors were systematic study by investigating the 3D finite element results.

Figures 5, 6, and 7 respectively show the curves that the vertical, horizontal and moment bearing capacity factors of the bucket foundations change with soil shear strength heterogeneity index $\kappa$ under different embedment ratios $L/D$. It can be seen from the figure that all the bearing capacity factors are decreasing with the increasing of $\kappa$, and the change curve is tending to gentle. This is mainly because the clay with the higher $\kappa$ has a lower undrained shear strength on the average along the bucket skirt. Furthermore, when $\kappa$ is a constant, all bearing capacity factors of the bucket foundation increase with the enlarging of $L/D$. That is because the increasing of embedment depth of bucket foundation can improve the resistance against loading.
In order for the convenience of designer reference and demand of study failure envelope under combined loading, we carried out fitting for finite element results of bucket foundation with honeycomb bulkheads, thereby obtaining Equations (3) - (5) which indicate the vertical, horizontal and moment bearing capacity factors, as shown below:

\[ N_{cv} = 8.59 \frac{L}{D} - 0.23 \kappa - 4.89 \left( \frac{L}{D} \right)^2 + 0.005 \kappa^2 + 0.07 \kappa \frac{L}{D} + 6.57 \]  \hspace{1cm} (3)

\[ N_{ch} = 7.4 \frac{L}{D} - 0.18 \kappa - 3.83 \left( \frac{L}{D} \right)^2 + 0.005 \kappa^2 - 0.04 \kappa \frac{L}{D} + 1.42 \]  \hspace{1cm} (4)

\[ N_{cm} = 0.99 \frac{L}{D} - 0.04 \kappa + 0.71 \left( \frac{L}{D} \right)^2 + 0.001 \kappa^2 - 0.02 \kappa \frac{L}{D} + 0.81 \]  \hspace{1cm} (5)

Equations (3)-(5) have taken the impact of embedment ratio \( \frac{L}{D} \) and soil shear strength heterogeneity index \( \kappa \) on bearing capacity factors into consideration. In the equations, \( 0.1 \leq \frac{L}{D} \leq 0.5 \), \( 0 \leq \kappa \leq 30 \), which basically covers the actual applying situation of composite bucket foundation.

Finally, the vertical ultimate bearing capacity \( V_{ult} \), the horizontal ultimate bearing capacity \( H_{ult} \) and the moment ultimate bearing capacity \( M_{ult} \) of the bucket foundation with honeycomb bulkheads can be obtained respectively by using the definition of the bearing capacity factors in Table 1 and the Equations (3)-(5).

3.2. Effect of honeycomb bulkheads on undrained bearing capacities

Previous studies [8-9, 16] have shown that the bulkheads may affect the bearing capacity of the bucket foundation to certain extent. In order to reflect the influence of honeycomb bulkheads on the undrained bearing capacity of the wide-shallow bucket foundation under uniaxial loading, the vertical
honeycomb bulkheads efficiency factor \( \delta_{N(L/D, \kappa)} \), horizontal honeycomb bulkheads efficiency factor \( \delta_{H(L/D, \kappa)} \), moment honeycomb bulkheads efficiency factor \( \delta_{M(L/D, \kappa)} \) were introduced in respectively, see Equation (6)-(8):

\[
\delta_{N(L/D, \kappa)} = \frac{N_{\text{inner}}}{N_{\text{bucket}}} \quad \tag{6}
\]

\[
\delta_{H(L/D, \kappa)} = \frac{N_{\text{inner}}}{N_{\text{bucket}}} \quad \tag{7}
\]

\[
\delta_{M(L/D, \kappa)} = \frac{N_{\text{inner}}}{N_{\text{bucket}}} \quad \tag{8}
\]

In the Equations: \( N_{\text{inner}} \), \( N_{\text{bucket}} \), \( N_{\text{inner}} \) respectively represent the vertical, horizontal and moment bearing capacity factors of bucket foundation with bulkheads under different \( L/D \) and \( \kappa \). \( N_{\text{inner}} \), \( N_{\text{bucket}} \), \( N_{\text{inner}} \) respectively represent the vertical, horizontal and moment bearing capacity factors of bucket foundation without bulkheads. Taking moment honeycomb bulkheads efficiency factor \( \delta_{M(L/D, \kappa)} \) as an example, if \( \delta_{M(L/D, \kappa)} > 1 \), the honeycomb bulkheads can enhance the moment bearing capacity of bucket foundation; if \( \delta_{M(L/D, \kappa)} = 1 \), it indicates that the honeycomb bulkheads have no effect on the moment bearing capacity of the bucket foundation.

Figure 8 shows the honeycomb bulkheads efficiency factors \( \delta_{V(L/D, \kappa)} \), \( \delta_{H(L/D, \kappa)} \), \( \delta_{M(L/D, \kappa)} \) for different \( L/D \) and \( \kappa \), respectively. It can be seen from the figure that, when \( \kappa = 0 \), \( \delta_{V(L/D, \kappa)} \), \( \delta_{H(L/D, \kappa)} \), and \( \delta_{M(L/D, \kappa)} \) are close to 1, it has no relation with the value of \( L/D \). That is to say, when the soft ground is homogenous clay, the honeycomb bulkheads basically have no impact on the undrained vertical, horizontal and moment ultimate bearing capacity of the bucket foundation.

Figure 8(a) shows that for non-homogenous clay \( (\kappa > 0) \), when \( L/D = 0.4 \) or \( L/D = 0.5 \), \( \delta_{V(L/D, \kappa)} \) is close to 1, the impact of the honeycomb bulkheads is not obvious at this time. Besides, the value of \( \delta_{V(L/D, \kappa)} \) is slightly greater than 1 when the \( L/D \) is relatively small, and increases as value of \( \kappa \) enlarges. When \( L/D = 0.1 \) and \( \kappa = 30 \), the vertical bearing capacity increased by about 5.0%. However, considering that the drawing deviation of the tangential lines may result in about 3% variation of ultimate bearing capacity by the tangent intersection method. In order to make conservative design, the impact of honeycomb bulkheads on the vertical bearing capacity of the bucket foundation can be ignored. Figure 8(b) shows that except for the case when \( L/D = 0.1 \) and \( \kappa = 30 \), \( \delta_{H} \) is slightly improved by around 5%, other cases are all close to 1. Also for safety design considerations, the undrained horizontal bearing capacity is considered to be unaffected by honeycomb bulkheads.

It can be seen from Figure 8(c) that, for non-homogenous clay, honeycomb bulkheads can significantly improve the moment bearing capacity of the bucket foundation. Unlike the performance of \( \delta_{V(L/D, \kappa)} \) and \( \delta_{H(L/D, \kappa)} \), the moment honeycomb bulkheads efficiency factor \( \delta_{M(L/D, \kappa)} \) increase greatly with the enlarging of \( \kappa \). And in addition, \( \delta_{M(L/D, \kappa)} \) firstly increases and then decreases with changes of \( L/D \), and \( \delta_{M(L/D, \kappa)} \) has obviously enhance when \( L/D = 0.2 \) or \( L/D = 0.3 \). At the occasion \( L/D = 0.2 \) and \( \kappa = 30 \), the moment bearing capacity of the bucket foundation can be enhanced for about 48% by the effect of honeycomb bulkheads.
4. Conclusions

In this study, the uniaxial undrained bearing capacity of wide-shallow bucket foundation with and without honeycomb bulkheads was analyzed through a great number of 3D finite element simulation, and evaluating the effect of the honeycomb bulkheads on improving the bearing capacity under different conditions. The conclusions of this study are shown as follows:

For homogenous clay ($\kappa$=0), the honeycomb bulkheads have little effect on the uniaxial undrained bearing capacity of the wide-shallow bucket foundation. For non-homogenous clay ($\kappa$>0), the undrained moment bearing capacity is obviously affected by honeycomb bulkheads and increases with the enlarging of soil shear strength heterogeneity, reaching the best improvement effect when $L/D=0.2$ or $L/D=0.3$. However, the setting of the honeycomb bulkheads has little effect on improving the vertical and horizontal bearing capacity of the bucket foundation, and its influence can be ignored.

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