



# Study on Bearing Behavior and Failure Envelope of the Foundation under Composite Loading in Soft Soil

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**Abstract.** Foundations of towering structures are usually subjected to complex multidirectional loads. For investigating the bearing behavior of bucket foundation in soft soil under vertical-horizontal composite loading, a three-dimensional numerical model was developed in this paper. Combining the Swipe loading method and the Probe loading method, the failure mechanism of the foundation under  $V-H$  composite loading was investigated. Under the combined  $V-H$  load, the horizontal bearing capacity of the barrel foundation increased with the increase of vertical load. The foundation failure envelope was obtained, and the results shown that the envelope expands gradually with the increase of the  $L/D$ . The  $V-H$  bearing envelope obtained is found to be even smaller with no-suction interface.

**Keywords:** Bucket foundation; Numerical simulation; Combined loading; Bearing behavior; Envelope

## 1 Introduction

China has a long coastline and is extremely rich in marine wind energy resources. In recent years, offshore wind power has been developing rapidly in China, thanks to the strong guidance of national policies [1]. However, offshore wind turbines, as a common towering structure, still face many challenges in the design of wind turbine foundations due to the complexity and variability of the marine environment [2]. Bucket foundation is still a new type of foundation, and its bearing behavior and damage mechanism under composite load in soft soil environment are still unknown, especially its damage envelope still need to carry out specialized research.

Bearing capacity characterisation is a crucial aspect of foundation design, with the majority of research conducted by scholars on bucket foundations focusing on this area[3-5]. Given that the bucket foundation is primarily subjected to vertical loading from dead-weight and horizontal loading caused by wind and waves, scholars typically concentrate on these two directions when analysing the bearing capacity of a bucket

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foundation under unidirectional loading[6]. The envelope method is typically employed to assess the combined loading effect[7].

To summarize, most of the existing studies focus on the bearing behavior of the foundation under simple loads, and there are relatively few studies on the bearing behavior and envelope of the bucket foundation under composite loads. This paper further investigates the bearing behaviour of bucket foundations when subjected to multiple coupled loading.

## 2 Numerical Modeling

Compared with field tests and indoor model tests, finite element numerical simulation is an efficient research method. By this method, the damage mechanism of foundation under loading can be effectively observed and the influence of related parameters can be analyzed. In the following section, this method will be used to carry out the study.

### 2.1 Geometry and Parameters

In order to better compare with model tests, the dimensions of the bucket foundation model are as follows: an outer diameter of 120 mm, an inside diameter of 114 mm, a height of 240 mm, and a depth of 235 mm, as illustrated in Fig. 1. In Fig. 1,  $\delta$  denotes the thickness of the bucket lid, which is set to 5 mm, and  $s$  denotes the thickness of the bucket wall, which is set to 3 mm. Because the foundation is much more rigid than a soft foundation, the bucket foundation is constructed using an all-steel structure, and plastic deformation is not considered. The Young's modulus is set to  $2.0 \times 10^5$  MPa, and the Poisson's ratio is set to 0.3. The foundation is set in a marine clay foundation. The study employed a Mohr-Coulomb mode based on the Tresca damage criterion to model the soil body, assuming the presence of three layers of foundation soil. The undrained shear strengths ( $S_u$ ) were 7 kPa, 12 kPa, and 16 kPa, respectively, with corresponding Young's moduli ( $E_s$ ) of  $150S_u$  and Poisson's ratios ( $\nu$ ) of 0.49.

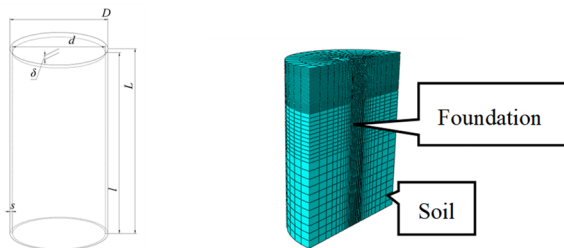


Fig. 1. Geometric modelling of the bucket foundation

### 2.2 Mesh and Contact Effect

As the bucket foundation model is axisymmetric, half-models are employed for analysis in this study. The mesh at the foundation part and the foundation in close proximity

to the foundation is taken as 0.1 times the diameter, while the mesh splitting step at other locations grows linearly in the radial direction. In this study, the simulation of the contact effect between the bucket foundation and the soil body employs the friction contact pair algorithm in ABAQUS software. The interface between the bucket foundation and the soil body is normal to the interface, adopting the "hard contact" configuration. In the context of modelling the contact effect, the empirically determined value of the frictional coefficient  $\mu$  is taken to be 0.3.

### 2.3 Finite Element Analysis Methodology

In order to obtain a more accurate load-displacement relationship curve, the displacement control method was employed for loading in this study. The methods of labelling the loads and displacements are shown in Table 1. In this paper, the subscripts "ult" are used to denote the ultimate capacity, and A and D denote the area and diameter of the top cover of the bucket foundation, respectively.

**Table 1.** Notation for loads and displacements

	Horizontal	Vertical
Load	$H$	$V$
Displacement	$h$	$v$
Dimensionless load	$N_H=H/AS_u$	$N_V=V/AS_u$
Normalised load	$H/H_{ult}$	$V/V_{ult}$
Normalised displacement	$h/D$	$v/D$

In this paper, two loading methods, Swipe method and Probe, are used to study the failure envelope of bucket foundation in  $V$ - $H$  loading plane, respectively. The loading methods are shown in Table 2.

**Table 2.** Finite element loading methods

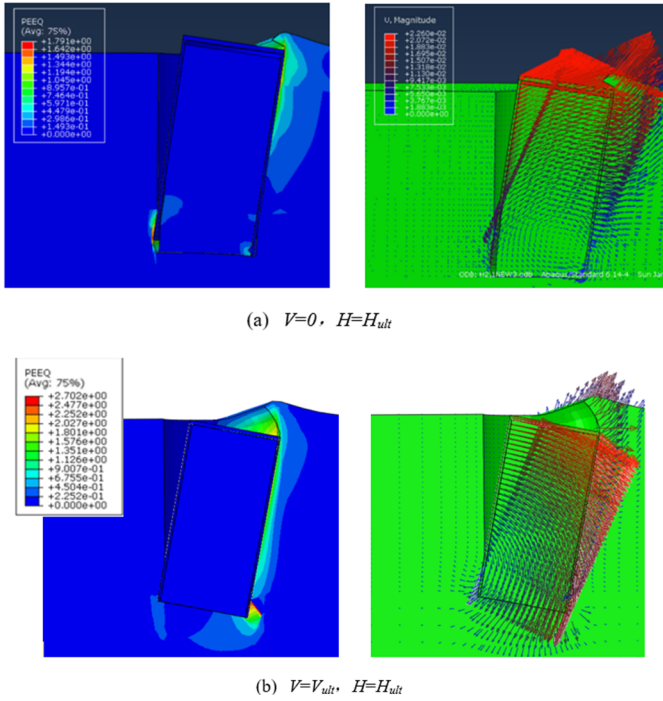
Group	Loading method	Loading sequence
Swipe	Displacement control	Apply $V$ first, then $H$
Probe-1	Displacement control	$h:v=1$
Probe-2	Displacement control	$h:v=0.5$
Probe-3	Displacement control	$h:v=10$
Probe-4	Displacement control	$h:v=1$
Probe-5	Displacement control	$h:v=20$

## 3 Analysis Results

### 3.1 Failure Mechanism of Foundations under $V$ - $H$ Combined Loading

In the previous section, the ultimate bearing capacity was determined. In this section, horizontal loading and gradually increasing vertical loading were applied at the

reference point of the top cover of the bucket foundation to study the foundation failure mechanism under V-H combined loading. The displacement vector diagram and equivalent plastic strain diagram of the bucket foundation were obtained, as shown in Fig. 2.



**Fig. 2.** Equivalent plastic strain distribution and displacement vector

As illustrated in Fig. 2, when subjected to combined vertical and horizontal loading, the bucket foundation is primarily subjected to rotational deformation. When the vertical loading is zero, the top cover of the bucket foundation is detached from the soil inside the bucket due to horizontal loading. As a gradually increasing vertical loading is applied, the centre of rotation of the bucket foundation gradually approaches the active side of the bucket wall. Upon reaching the limit value for vertical loading, the plastic strain of the bucket foundation will be concentrated at the bottom of the bucket in the direction of horizontal loading.

### 3.2 V-H Envelopes

Fig. 3 illustrates the normalised failure envelope of the bucket foundation, obtained using both the Probe and Swipe methods of loading. The normalised damage envelope curves obtained from the two loading methods exhibit a comparable trend. Prior to the application of vertical loading reaching  $0.6 V_{ult}$ , the horizontal bearing capacity of the bucket foundation is positively correlated with the vertical loading. When the vertical loading equals to  $0.6 V_{ult}$ , the horizontal bearing capacity reaches a peak value of 1.163

$H_{ult}$ . However, as the vertical loading continues to increase, the horizontal loading capacity gradually decreases, and the bucket foundation becomes mainly vertically loaded.

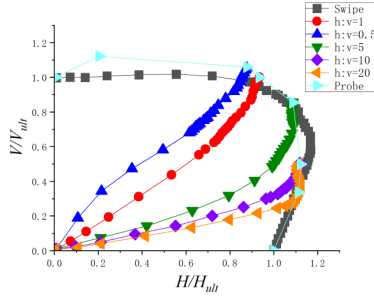


Fig. 3. V-H failure envelopes obtained from different loading methods

### 3.3 Effect of Bucket-Soil Interface on the $V-H$ Envelope

The way soil interacts with a foundation can be divided into two types: suction contact and no-suction contact. In suction contact, the soil sticks to the foundation, while in no-suction contact, the soil can move away from the foundation. The foundation can provide suction to the soil, or it can detach from the soil vertically. In the latter case, the soil can't provide suction to the foundation. Fig. 4 shows the dimensionless bearing envelope of the bucket foundation for the two models. The  $V-H$  bearing envelope, derived from the suction contact model, exhibits a proclivity towards a reduction in vertical loading capacity with increasing horizontal loading. Furthermore, the envelope is observed to be larger than that derived from the no-suction contact model.

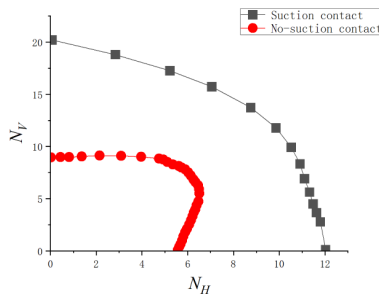


Fig. 4. V-H bearing envelope under suction contact and no-suction contact effects

## 4 Conclusion

The main conclusions are as follows:

1) The horizontal bearing capacity of the foundation is found to be positively correlated with the vertical loading, with the horizontal bearing capacity reaching a peak value of  $1.163H_{ult}$  when the vertical loading reaches  $0.6V_{ult}$ .

2) It can be observed that with the increase of the bucket  $L/D$  ratio, the vertical loading for horizontal loading capacity enhancement gradually decreased, while the bearing envelope of the bucket foundation gradually expanded.

3) When calculations using no-suction interface are performed, the  $V-H$  bearing envelope obtained is found to be even smaller.

The soil layer in the actual project is more complicated. The bearing behavior of foundations in the presence of sand and clay layers together still requires further research.

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