Numerical Analysis of Cyclic Bearing Capacity of Suction Bucket Foundation Based on Elasto-plastic FEM

Ke Wu

Ph.D., Lecturer, Research Center of Geotechnical and Structural Engineering; Shandong University; Jinan; Shandong 250061, P. R. China
e-mail: wuke@sdu.edu.cn

Mingyue Ma

Shandong University of Science and Technology, Qingdao, Shandong 266510, P. R. China
e-mail: shouhouxiaoke@163.com

Rong Chen

State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, and Institute of Geotechnical Engineering, School of Civil and Hydraulic Engineering, Dalian University of Technology
Dalian, 116024, P.R. China

ABSTRACT

Suction bucket foundation is a new-type cost-effective offshore foundation, especially applicable for marginal field oil extraction, which is usually subjected to varied combined loads. However, studies on cyclic bearing capacity of suction bucket foundation are not sufficient to work out a reasonable analysis and computational procedure. Based on the concept of cyclic shear strength of soil, the paper applies Andersen analytical method on gravity foundation and combines cycle strength of soft soil and Mises yield criterion to determine bearing capacity of suction bucket foundation under cycle loading pattern. Therefore, a 3D quasi-static finite element method for assessing cyclic bearing capacity of offshore foundations or structures is numerically implemented in the framework of the general-purpose FEM software package ABAQUS. The numerical results computed by the proposed method indicate that cyclic bearing capacity has been reduced remarkably due to the cyclic softening effect induced by wave loading with respect to ultimate bearing capacity.

KEYWORDS: bucket foundation; 3D finite element method; bearing capacity; varied combined loads; quasi-static analysis

INTRODUCTION

As more and more exploration and development have been carried out in deep waters, alternative types of foundations are being employed to take place traditional systems for offshore facilities, such as gravity foundation, skirt foundation, towards design in increasingly deep water and hostile loading environments. Due to the economic and repetitive usability of bucket foundation, it has attracted much attention of oil companies in recent years [1-5]. In addition, in-situ installation of the bucket foundation is relatively convenient by active suction installation method [6]. The suction bucket foundation is composed of a cylinder with open bottom and sealed top on which air exhausting is held. The bucket is sunk to the seabed by virtue of its own weight and then exhaust is conducted by vacuum pump through the holes to achieve negative pressure in the cylinder. By means of the difference of pressures inside and outside the cylinder, the cylinder is pushed into soil until the cavity is filled with the soil entering from bottom. Therefore, suction bucket foundation is penetrated into the soil by means of suction. When the platform needs to be removed, the cylinder can be drawn out by pumping air into the cavity. Consequently, the suction bucket foundation can be used repetitively [7].

Engineers are often required to evaluate the behavior of offshore foundations subject to the monotonic load or combined loads (i.e. horizontal loads, H, and moments, M, in addition to central vertical loads, V). This is absolutely true in the offshore industry, where, during a storm, environmental wind and wave forces impose significant horizontal loads and overturning moments on offshore foundations, as well as alter the vertical load [8]. Recently, many researchers seek to characterize a failure envelope in V-M-H loading space to describe the foundation response transformation from safe condition to failure state. Under different combined loads, such as horizontal and vertical loads, vertical and moment loads, horizontal and moment loads, the bearing capacity of foundation is beyond the ultimate bearing capacity and instability. In the load spaces, the ultimate bearing capacities composite a space curved face under different combined loads, which is named as the failure envelope. Some researchers [4, 9, 10] have analyzed the combined loading response of foundations using plasticity methods based on an assumed yielding envelope. A yielding surface is introduced, relating the applied vertical, moment and horizontal loads, whereby

$$f\left(\frac{V}{As_u},\frac{H}{As_u},\frac{M}{ABs_u}\right)=0 \tag{1}$$

Where A is the area of the foundation, B is diameter or width and Su is representative soil strength. Some researchers [11-13] have suggested various empirical curve-fits for the failure envelope based on centrifuge or 1g test date. However, the bearing capacity behavior of suction bucket foundation subjected to a combination of static and cyclic loads is one of the key issues in construction and design of offshore structures and facilities. Cyclic loading may reduce the shear strength of the soil and make foundation deformed largely. For example, the experience from plate-loading tests shows the bearing capacity under cyclic loading which is 70% of that under static loading [14]. Failure during cyclic loading may accompany with large horizontal or rotational cyclic displacements, large cyclically induced average displacement (e.g., settlements), or a combination of large cyclic and average displacements. Moreover, the cyclic bearing capacity under varied combined loads is evaluated by considering the features of cyclic or instantaneous loads and the cyclic softening effect of soil. It is important that ultimate bearing capacity and failure envelopes of bucket foundation under cyclic loading are considered in design analyses.

Based on the concept of cyclic shear strength of soil, the present paper applies Andersen's analytical method on gravity foundation with combining cyclic strength of soft soil and Mises yield criterion to determine cyclic bearing capacity of suction bucket foundation under cycle loading pattern. Therefore a 3D quasi-static finite element method for assessing cyclic bearing capacity of offshore foundations or structures is numerically implemented in the framework of the general-purpose FEM software package ABAQUS. A number of three-dimensional nonlinear FEM computations for cyclic bearing capacity are conducted and compared with ultimate bearing capacity under combined loads. Then the results from analysis and comparison are used to evaluate the bearing capacity of bucket foundation subjected to cyclic loading, which will provide referential resources for the design and construction.

FINITE ELEMENT MODEL

Finite Element Code ABAQUS/Standard

The commercial finite element code ABAQUS/Standard has been used to numerically simulate the behavior of suction bucket foundation in soft soil. ABAQUS is a general-purpose finite element code for the static and transient response of 2- and 3-dimensional systems. It supplies an extensive library of elements that can model virtually any geometry. ABAQUS also contains a wide range of material models that can simulate the behavior of most typical engineering materials. Moreover, ABAQUS/Post, an interactive and graphical postprocessor provides a wide range of options for interpreting the results [15].

Geometry and Material Parameters

The bucket foundation of width D and depth L used for the analysis is assumed to be rigid, interacting with the surrounding of the foundation soil. The contact between the footing and the foundation soil is assumed to be rough [16]. Used for bucket structure is a linear elastic constitutive model with a modulus of elasticity of E=210GPa and Poisson's ratio of ν=0.125. For subsoil, the linearly elasto-perfectly plastic constitutive model obeying to Mises' yield criterion is employed. The Poisson's ratio of soft soil is taken as ν=0.49 and the deformation modulus is assumed to maintain a constant modulus ratio, E_u/s_u, of 500. Under the undrained condition, soft soil is assumed to obey to Mises' yield. Then, the generalized shear stress q of random point interior of foundation is equivalent to equivalent static stress, $\sigma_s = \sigma_1 - \sigma_3$, in the cyclic triaxial test or straight shear test

$$q = \sigma_s = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2} \tag{2}$$

The contact pair algorithm in the ABAQUS is employed to simulate contact features of the interface between caisson and soil [15]. Coulomb's friction law is used to estimate tangential ultimate frictional resistance. When shear stress on the contact surface is less than the ultimate frictional resistance, both are stuck together and no slip happens. On the contrary, when shear stress on the contact surface exceeds the ultimate frictional resistance, slip happens along the contact surface. Contact in normal direction of the interface is considered the hard contact or it is assumed that under the undrained condition, the separation of normally consolidated clay from the bucket wall is not allowed.

Finite element mesh

Based on FEM packages ABAQUS, a three-dimensional finite element mesh for analysis of bucket foundations is shown in Figure 1, considering the symmetry of both geometrical and loading conditions, half portion of the structure with foundation is used to establish the finite element model in order to reduce computational effort. In order to eliminate far-away boundary effect, the soil within 10 times of radium of foundation radially and 6 times of height of foundation in depth is included into the computational region. To estimate the initial stresses, it is assumed that after the cylinder penetrates into the soil, the contact surface between cylinder and surrounding soil is a horizontal plane. The density of bucket foundation is taken to be the same as that of surrounding soil. The structure and the soils inside and outside the bucket are all simulated by 20-node brick elements [17].

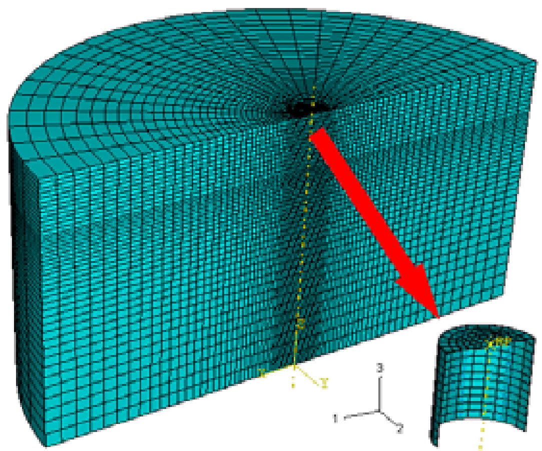


Figure 1: Finite element model used in analyses

FINITE ELEMENT ANALYSIS METHOD

Cyclic Shear Strength

The dynamic response and stability of offshore foundation subjected to cyclic forces owning to wave are of importance to marine soil mechanics and foundation engineering. Wave loads are different from earthquake, whose operation time is longer than that of earthquake. Empirical reduction coefficient method is always approximate to evaluate the bearing capacity of foundation subjected to cyclic loading in offshore foundation design. In fact, the strength of soil is softening due to the cyclic loading, resulting in the decrease of the ultimate bearing capacity of foundation. However, studies on cyclic bearing capacity of suction bucket foundation under combined loading mode are not sufficient to work out a reasonable analysis and computational procedure. Based on studies of the stability and ultimate bearing capacity of gravity foundation under cyclic loading, Anderson has presented the concept of cyclic shear strength of soil. The cyclic shear strength $\sigma_{f,cy}$ may be defined as the sum of the initial and cyclic shear stresses that cause failure after a given number of cycles [14, 18]

$$\sigma_{f,cy} = \sigma_s + \sigma_d \tag{3}$$

The cyclic shear strength can be calculated as following. Firstly, the initial shear stresses of soil elements can be calculated by FEM corresponding to actual loads. Secondly, the cyclic shear strength subjected to different stresses can be estimated by the cyclic triaxial test [18]. Finally, the equivalent relationship between stress-state in triaxial test and actual stress-state in foundation will be considered by equation (2). Then, the cyclic strength can be evaluated under the given cyclic numbers. In the paper, the curve of cyclic strength refers to the experimental results by Wang [18].

Displacement Controlled Method

In the finite element analysis, load is usually applied to the load controlled method or the displacement controlled method. Being different from the load controlled method, the displacement controlled method can simulate the post-failure response. From the load-displacement response of footing, it may be concluded that the soil foundation has attained its limit equilibrium state. In this state, the slope of load-displacement curve tends to vanish, so that the bucket foundation displacement continually increases without additional increment of the applied load. The applied load corresponding to the limit equilibrium state is recognized as ultimate bearing capacity [19]. Therefore, in this paper, the ultimate bearing capacity of suction bucket foundation founded in the homogeneous soil strata under the undrained conditions subjected to vertical (*V*), horizontal (*H*) and moment (*M*) loading respectively is determined by displacement-controlled method. The application point of displacement components is assumed at the midpoint of the bucket foundation shown in Figure 2, which include a vertical displacement w, a horizontal displacement u and a rotation angle θ. Through studies on ultimate bearing capacity of bucket foundation subjected to different cyclic numbers, effect of cyclic numbers to ultimate bearing capacity can be estimated by the displacement controlled method.

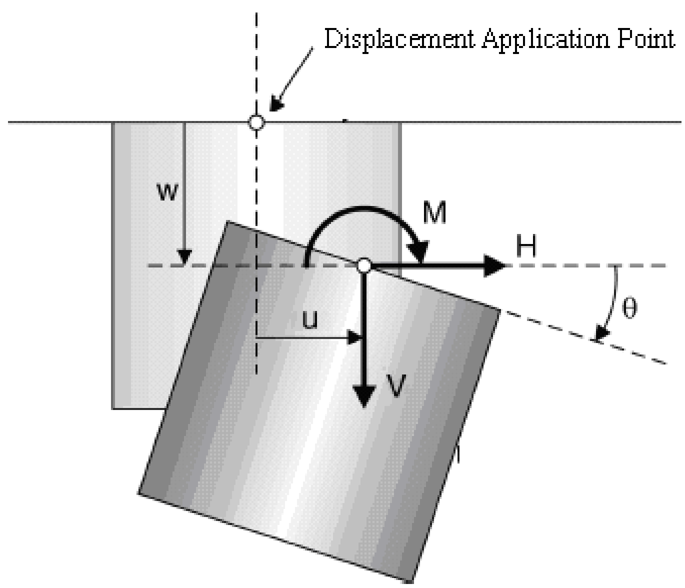


Figure 2: Sign convention of displacements and forces

Based on the constitutive model and the computational model, the ultimate bearing capacity of bucket foundation under monotonic loading can be defined by displacement controlled [20].

Swipe Test Procedure

Swipe test procedure was originally suggested and applied in a small-scale model tests by Tan [4] and then widely applied into practice [21]. The loading procedure includes two loading steps which are illustrated in Figure 3, an example of search of failure envelope in *V-H* loading plane. (1) an incremental vertical displacement δv is imposed vertically from the initial state to the state that vertical load is no longer increases with the increase of displacement. (2) Under the unchanged vertical displacement, horizontal displacement δh is incrementally exerted until the horizontal load no longer improves as the increase of horizontal displacement. The loading track formed in such a loading paths may be taken as the approximation of the potential failure envelope in *V-H* loading plane. The loading may be imposed by an alterative way, i.e., first, the incremental horizontal displacement is exerted to conduct loading analysis in horizontal direction and then vertical displacement is exerted to conduct vertical loading analysis under unchanged horizontal displacement. Therefore, two loading tracks may be established along the *V-H* loading path and the *H-V* loading path in Swipe test procedure. Both tracks are integrated to give envelope of bearing capacity of suction caisson foundation [7].

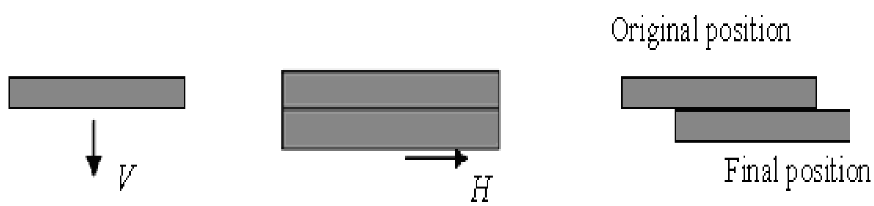


Figure 3: Swipe test procedure (*V-H*)

Approximate lower limit solutions corresponding to every combination of loads in failure envelop subjected to combined loads will be found by Swipe test procedure in FEM. Moreover, by making use of cyclic shear strength concept, the failure envelopes of bucket foundation under cyclic combined loads can be gained.

Sign Convention and Nomenclature

The sign convention for displacements and loads presented in this paper obeys to a right-handed axes and clockwise positive convention which was proposed by Butterfield [22]. The notation adopted for loads and displacements is shown in Table 1.

Table 1: Summary of notation for loads and displacements

Load	Horizontal H	Vertical V	Rotational M
Ultimate Load	H_{ult}	V_{ult}	M_{ult}
Dimensionless Ultimate Load	$h=H/(AS_{u0})$	$v=V/(AS_{u0})$	$m=M/(ADS_{u0})$
Normalized Load	$\overline{h} = H/H_{ult}$	$\overline{v} = V/V_{ult}$	$\overline{m} = M/M_{ult}$
Displacement	u	w	θ

CYCLIC BEARING CAPACITY

Fan Q. L. and Luan M. T. [17] have used this method to evaluate the vertical bearing capacity of shallow foundation. Based on the necessity of considering the shear strength softening, three-dimensional nonlinear FEM analysis of deeply-embedded large-diameter cylindrical structure in soft ground has been developed by the proposed method. Therefore, the ultimate bearing capacity of foundation against wave loading has been evaluated and compared with that of foundation under monotonic loading.

In order to evaluate the proposed method correct, the vertical cyclic bearing capacity of shallow foundation has been analyzed based on elasto-plastic FEM. Used for homogeneous soft soil, the linearly elasto-perfectly plastic constitutive model obeying Mises's yield criterion is employed. The shear strength and Poisson's ratio of soft soil are taken respectively as Su=8.66kPa and ν =0.49. And the deformation modulus is assumed to maintain a constant modulus ratio, Eu/Su, of 500. The cyclic strength curves refer to the cyclic test curves by Wang [18] and the cyclic number is 1000.

Distribution of the ratio of static shear stress computed for surface foundation is shown in Figure 4. The FV1, $\mathrm{FV1} = \sigma_s / \sigma_{f,cy}$, is defined as the ratio of the static shear stress computed. Relationship between the coefficient of vertical bearing capacity and normalized displacement of foundation base computed by different methods is shown in Figure 5. The A, B, d are defined respectively as the area of the top of foundation, width of foundation and displacement of foundation. The Vs and Vd are defined respectively as static and cyclic vertical loading. It can be found that the method by the paper accepted is appropriate for analyze the cyclic strength of foundation. The coefficient of vertical bearing capacity against cyclic loading decreases by 28% of that under monotonic loading.

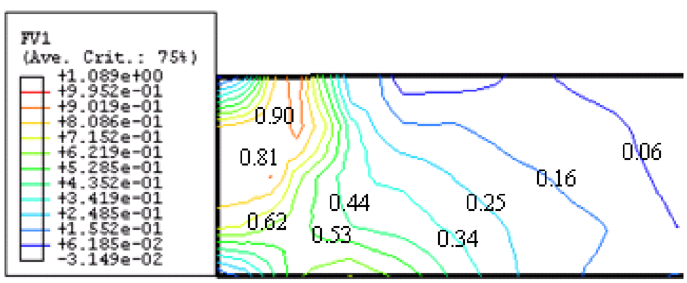


Figure 4: Distribution of the ratio of static shear computed for surface foundation

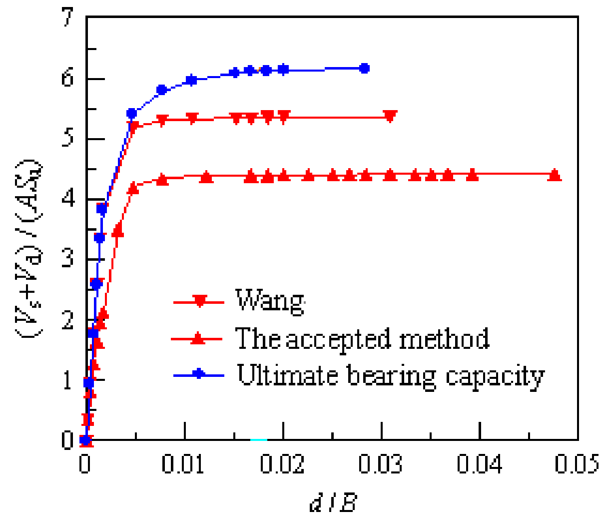


Figure 5: Relationship between the coefficient of vertical bearing capacity and normalized displacement of foundation base computed by different methods

NUMERICAL RESULTS

During a storm, the soil elements will be against cyclic stress σ_d. If the combination of static and cyclic stresses, $\sigma_s + \sigma_d$, exceeds the cyclic shear strength, the soil elements will be yielding failure. The stresses of soil elements will be redistributed and the zones of yielding failure will diffuse into the adjacent elements, which cause those soil elements to damage and failure. If the zones of destruction become a whole zone, the bucket foundation will be destabilized.

After installation of bucket foundation, the footing soil is subjected to the weight of platform structures and foundation itself. Under the self-weight stress, the vertical displacement of foundation is generated, and the maximum displacement occurs in the center of foundation and decreases gradually with distance from the center of foundation as shown in Figure 6. The initial stresses of foundation are improved with the increasing depth as shown in Figure 7.

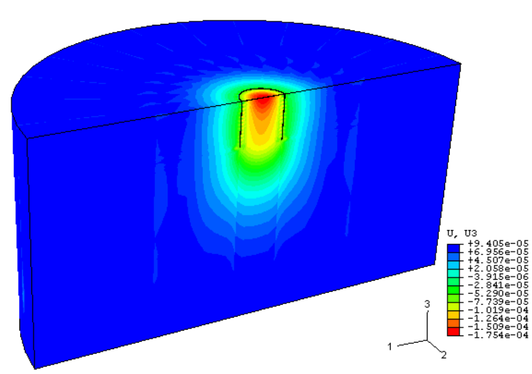


Figure 6: The displacement under the self-weight stress

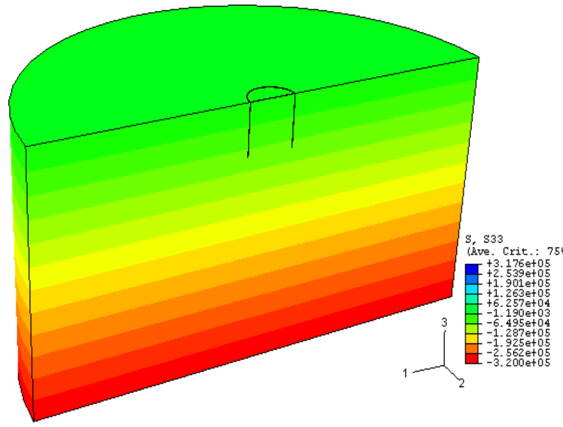


Figure 7: The initial stresses under the self-weight stress

Ultimate bearing capacity

Figure 8 shows a typical load-displacement curve and it might be used to measure a bucket foundation under monotonic horizontal load. The curve consists of an elastic portion, a region of transition from mainly elastic to mainly plastic behaviour; a plastic region is a place where the load increases very little while the deflection increases manifold. If idealizing the soil as a perfectly plastic medium and neglecting the changes in geometry, a condition will be get, in which displacements can increase without limitation while the load is held constantly. A load computed on the basis of this ideal situation is called plastic limit load or collapse load. This hypothetical limit load usually gives a good approximation to the physical plastic collapse load or the load at which deformations become excessive [23]. The ultimate bearing capacity of bucket foundation under monotonic load can be determined by this method.

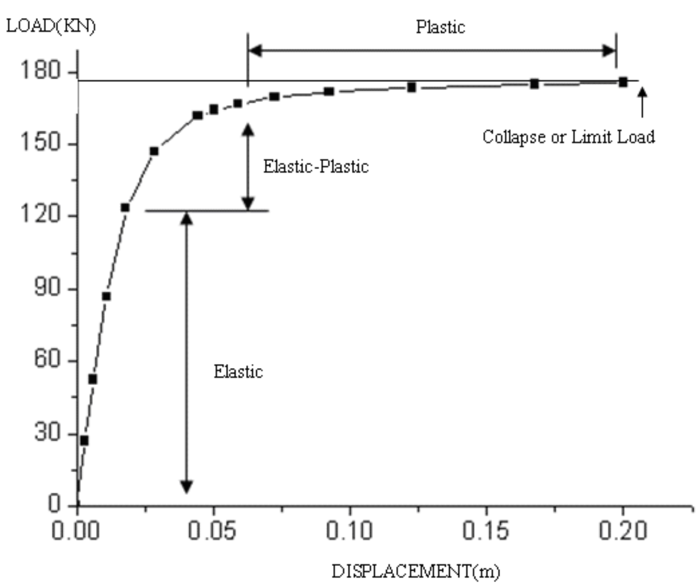


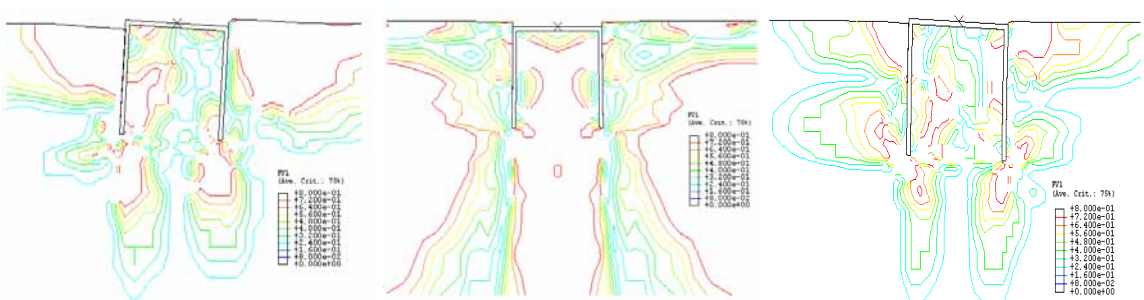
Figure 8: A typical plastic collapse phenomenon and definition of limit load

Based on the finite element results, a summary of the dimensionless ultimate loads observed are shown in Table 2. It can be found that (1) The dimensionless ultimate loads of bucket foundation subjected to monotonic horizontal, vertical and moment loads are respectively 3.54, 7.48 and 2.46 when the cyclic effect is not considered. (2) If the cyclic effect is considered, the dimensionless ultimate loads of bucket foundation will reduce with the increase of the cyclic numbers. For example, the dimensionless ultimate load of bucket foundation is the maximum of all cyclic numbers considered when cyclic number is 100. The dimensionless ultimate loads of bucket foundation are respectively 3.02, 6.38 and 1.99, which respectively reduce 14.7%, 14.7% and 19.1% compared with the dimensionless ultimate loads of bucket foundation subjected to monotonic loads. Moreover, the dimensionless ultimate load of bucket foundation is the minimum of all cyclic numbers considered when the cyclic number is 2000. The dimensionless ultimate loads of bucket foundation are respectively 2.39, 5.21 and 1.59, which respectively reduce 32.5%, 30.4% and 35.4% compared with the dimensionless ultimate loads of bucket foundation subjected to monotonic loads.

Table 2: Summary of dimensionless ultimate loads by FEM

Dimensionless Ultimate Loads	Cycle Number				
	N=0	N=100	N=500	N=1000	N=2000
$h=H/(AS_{u0})$	3.54	2.91	2.56	2.45	2.31
$v=V/(AS_{u0})$	7.48	6.38	5.67	5.48	5.21
$m=M/(ADS_{u0})$	2.46	1.99	1.74	1.68	1.59

Then, the distributions of the ratios of static shear stress computed subjected to cyclic loads are shown in Figure 9 corresponding to a cyclic number of 1000. It can be found that (1) the cyclic shear strength is distributed non-uniformly subjected to cyclic loads, which causes the bearing capacity of bucket foundation decrease. (2) Under horizontal cyclic load, the integrated scoop-shaped distribution of the ratios of static shear stress is initiated at the bottom of bucket foundation. At the same time, a passive wedge is produced in the side of bucket foundation along the loading direction. While in the side of bucket foundation along the direction contrary to horizontal loading, a separation is induced in the so-called active area. (3) Under vertical cyclic load, an almost symmetrically distribution of the ratios of static shear stress is initiated at the bottom of bucket foundation. Substantial shear deformations occur along both contact sides of the bucket and soils. (4) Under cyclic moment, it seems that the distribution of the ratios of static shear stress is similar to that happens under horizontal cyclic loading.



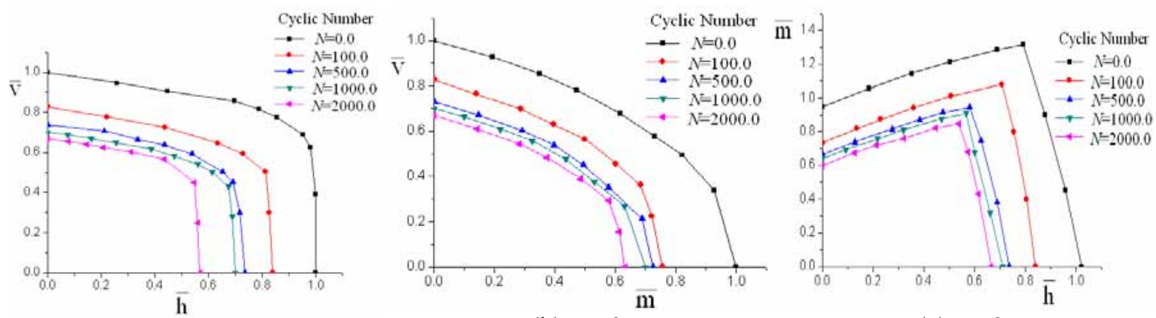
(a) Horizontal cyclic load (b) Vertical cyclic load (c) Cyclic moment load

Figure 9: Distribution of the ratios of static shear stress computed

Moreover, the cyclic bearing capacity of bucket foundation reduces with the increase of the cyclic numbers and cyclic bearing capacity which reduces 30% corresponding to those under monotonic loads.

Failure envelopes

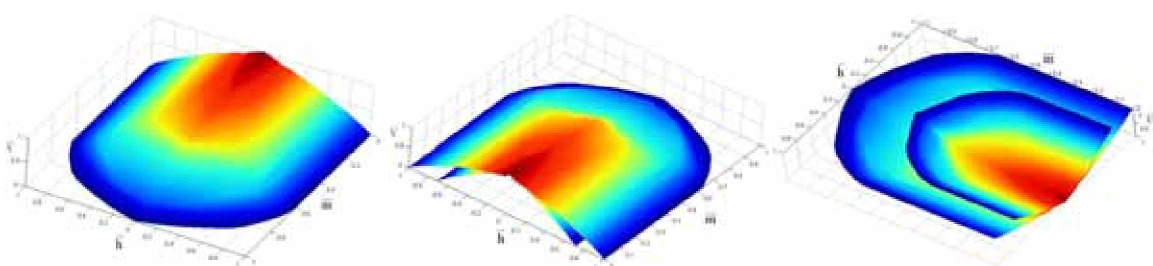
The failure envelopes subjected to combined loads and varied combined loads are shown in Figure 10. It can be seen that (1) failure envelopes under varied combine loads are inside of those under combined loads and the shapes of failure envelopes are similar. (2) The shapes of failure envelopes reduce with the degree of cyclic number increasing. (3) Comparing with the ultimate bearing capacity subjected to combined loads, the bearing capacity under varied combined loads decrease approximately 30%, which is basic concordant to the results under monotonic loads.



(a) *M*=0 (b) *H*=0 (c) *V*=0

Figure 10: The failure envelope of foundation in different load spaces

Moreover, the 3-dimensional failure envelope of foundation in the *V-H-M* load space as the degree of cyclic number increase is shown in Figure 11. As a result of the increase of cyclic numbers (N), for example, N=0.0, N=1000.0, the soil cyclic strength reduces which causes the bearing capacity of foundation weakened. It is clear that the failure envelopes reduce with the increase of moment loading, and finally, become a point, which form yield surfaces similar to a 1/4 ellipsoid. Based on the failure envelope of foundation in the *V-H-M* load space, the working performance of bucket foundation can be evaluated. For example, if the actual combination of loads is within the yield surface, the bucket foundation will be stability. However, if the actual combination of loads is on or beyond the yield surface, the bucket foundation will be destabilized which may be influenced the platform working.



(a) Front (b) Back (c) Bottom

Figure 11: 3-dimensional failure envelope of foundation in the V-H-M load space

NUMERICAL RESULTS

By integrating the general-purpose FEM analysis package ABAQUS with the Swipe test procedure of loading based on displacement-controlled manner, the failure mechanism and bearing capacity feature of suction bucket foundation subjected to varied combined loads are investigated. It is addressed that the cyclic bearing capacity of the bucket foundation against cyclic loading is substantially dependent on cyclic number. Through numerical computations and comparative analyses based on FEM, the three-dimensional failure envelope of suction bucket foundation can be established by using the proposed method in order to evaluate the stability of foundation under varied combined loading. It can be found that the failure envelopes form yield surfaces similar to different 1/4 ellipsoid, which is narrowed as the degree of cyclic number increase.

Since the accuracy of finite element analyses may be affected by density of meshes divided, a certain man-made errors probably exist in judgment of limit-equilibrium state and ultimate capacity. Nevertheless these errors will be allowable in engineering practice.

ACKNOWLEDGEMENTS

The financial is supported by Open Foundation of Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering (081230) and China Postdoctoral Science Foundation (200904501211).

REFERENCES

1. Aas, P. M., Andersen, K. H. (1992) Skirted foundation for offshore structure. Ninth Offshore South East Asia Conference, Singapore. World Trade Center Singapore, Singapore, 1-7.
2. Dyme, W., Houlsby, G. T. (1998) Drained behavior of suction caisson foundations on very dense sand. OTC1099:765-782.
3. Senpere, D., Auvergne, G. A. (1982) Suction anchor piles-a proven alternative to driving or drilling. OTC4206:483-493.
4. Tan, F. S. (1990) Centrifuge and theoretical modeling of conical footings on sand. PhD thesis, Cambridge University, UK
5. Butterfield, R. and Gottardi, G. (1995) Simplifying Transformations.
6. Deng, W. and Carter J. P. (2000) A theoretical study of the vertical uplift capacity of suction caissons. Proceeding of the Tenth International Offshore and Polar Engineering Conference, 2:342-349.
7. Wang, ZH. Y., Luan, M. T., Wang, D. (2006) Ultimate bearing capacity of suction caisson foundations in undrained soils. Recent Development of Geotechnical and Geoenvironmental Engineering in Asia, 229-234.
8. Cassidy, M. J., Byrne, B. W., Randolph, M. F. (2004) A comparison of the combined load behaviour of spud-can and caisson foundations on soft normally consolidated clay. Geotechnique, 54(2), 91-106.

9. Houlsby, G. T. and Martin, C. M (1992) Modeling of the behaviour of foundations of jack-up units on clay. Proc. Wroth Memorial Symp. "Predictive Soil Mechanics", 339-358.
10. Bye, A., Erbrich, C., Earl, K. (1995) Geotechnical design of bucket foundation, OTC7793:869-883.
11. Dean, E. T. R., James, R. G., Schofield, A. N., Tan, F. S. C. and Tsukamoto, Y., (1992): The bearing capacity of conical footings on sand in relation to the behaviour of spudcan footings of jack-ups. Proc. Wroth Memorial Symp. "Predictive Soil Mechanics", 230-253.
12. Martin, C. M. (1994) Physical and numerical modeling of offshore foundations under combined loads, PhD thesis, University of Oxford, UK.
13. Murff, J. D. (1994): Limit analysis of multi-footing foundation systems, Proc of the 8th Int. Conf. on Computer Methods and Advances in Geomechanics, 1, 223-244.
14. Andersen K H, Kleven A, Heien D. (1988) Bearing capacity for foundation with cyclic loads. Journal of the Geotechnical Engineering Division, ASCE, 114(5):540-555.
15. Hibbitt, Karlsson, Sorensen (2002) ABAQUS Scripting User's Manual (Version6.3), Pawtucket: HKS.
16. Fan, Q. L., Luan, M. T., Yang, Q., Qi, J. F. (2006) Analyses of bearing capacity for deeply-buried large-diameter cylindrical structure on soft clay considering cyclic-softening effect. Journal of Dalian University of Technology, 40(5):702-706.
17. Fan Q. L., Luan M. T., Yang Q., Wu K., Wang ZH. Y., (2006) Effect of soil strength nonhomogeneity on bearing capacity of deeply-embedded large-diameter cylindrical structure on soft ground against lateral loads. Recent Development of Geotechnical and Geoenvironmental Engineering in Asia, 179-182.
18. Wang J H, Li C, Moran K. (2005) Cyclic undrained behavior of soft clays and cyclic bearing capacity of a single bucket foundation. Proceedings of the 15th International Offshore and Polar Engineering Conference, Seoul, Korea, 2: 377-383.
19. Zhao, S. F., Luan, M. T., Lü, A.Z. (2005) Numerical analysis of bearing capacity of foundation under combined loading, Proceedings of the First International Symposium on Frontiers in Offshore Geotechnics (ISFOG), 499-505.
20. Wu, K., Luan, M. T., Fan, Q. L. (2006) Numerical analyses of bearing capacity of suction bucket foundation. Recent Development of Geotechnical and Geoenvironmental Engineering in Asia, 213-218.
21. Taiebat, H. A.and Carter, J. P. (2005) Interaction of forces on caissons in undrained soils. Proceedings of the Tenth International Offshore and Polar Engineering Conference, 625-632.
22. Butterfield, R., Houlsby, G.T., Gottardi, G. (1997) Standardised sign conventions and notation for generally loaded foundations. Geotechnique, 45(5):1051-1054.
23. Chen, Wai-fah. (1975) Limit analysis and soil plasticity. New York.