Finite Element Analysis of Variable-diameter Single Pile under the Condition of Marine

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ABSTRACT

In this research, the mechanical characteristics of variable-diameter single pile under the combination of wind, wave and tidal current actions are studied. Take a variable-diameter single pile of CB11F platform as an example, finite element analysis is analyzed using ANSYS program. The parameters which affect the single pile response are analyzed, such as environmental loads, soil condition and position of variable-diameter. And the model of variable diameter section is simplified, from which the pile displacement and body stress under the action of wave and current are derived. Comparing the results with that of the equal-diameter pile model, the displacement and stress of variable-diameter pile model reduce more than 20%.So that, the effectiveness of the variable-diameter measure is verified in improving the mechanical properties of the pile

KEY WORDS
ocean engineering, variable-diameter，single pile, horizontal bearing capacity

INTRODUCTION

In the rolling developmental model of Chengdao Oilfield, independent piles are used (Wang, 2003). Both in structure and economy, it is more suitable for the marine. However, with the depth increasing, the loads increase gradually. The top of the platform will have a significant shaking. In order to solve this problem, the company has developed a new type of piles called variable-diameter single pile.

The adjustable location of the pile is generally 1m below the surface of sea, which can effectively reduce the load area of the waves, the currents and the ice. As a result,the horizontal load is reduced.

In this paper the pile-soil model is appropriately simplified. The dynamic calculation of single piles is done with the PIPE59 unit in ANSYS program (Li, 2003). The variable-diameter single pile is more effective than the normal pile,which can be known by comparing the results.

HORIZONTAL BEARING FORCE CALCULATION

Horizontal bearing force of piles depends on the stiffness,the strength,the depth of piles and the characteristics of the soil. The pile, which is similar to the long beam on the foundation, can be calculated by the Foundation Reaction method. Take the pile's axis for z-axis,and take the horizontal soil surface for y-axis. According to the deflection theory of beams, we can get the deflection differential equation of single piles:

$$EI\frac{d^4y}{dz^4}+p(y,z)=0 \tag{1}$$

Where: y is the pile's deflection of depth z, $p(y, z)$ is the reaction on a unit length of the pile, who's equation is :

$$p(y,z)=kz^n y^m \text{, or } p(y,z)=k(z)y^m \tag{2}$$

Where: $k(z)$ is the coefficient of the foundation.

The 3 methods of Calculating horizontal bearing capacity of piles, according to the different sub grade reactions $p(y, z)$, are the ultimate bearing capacity of foundation method,the elastic sub grade reaction method and the composite ground reaction method (Yokoyama , 1984)(the *p-y* curve method).

The elastic sub grade reaction method and the composite ground reaction method(the *p-y* curve method) are widely used in the current project. The former is mainly used in the flexibility analysis of lateral load and the latter is mainly used in the elastic-plastic analysis. Since the *p-y* curve method [API PR,1991;CSS ,1992] accurately reflects the inelastic nature of soil and the destructive phenomenon arising from soil's surface, it is commonly used in the piles of the marine platform.

FINITE ELEMENT MODEL OF INDEPEDENT PILE

Selection of Units

The finite element model is established by using ANSYS Program. The pile's platform is simulated into the dimensional tube, beam and combinational board structure (Zhang,2005). The main units used in models are: PIPE59 element simulates the pile above the soil surface; PIPE16 element simulates the pile below the soil surface; COMBIN39 element simulates the soil.

- **PIPE59 Unit**：PIPE59 unit is a tube-shaped unit which is similar to the dimensional beam. It can consider the axial tension and compression, reverse and bending deformation. Meanwhile, it expands the marine environmental load, that is, buoyancy, waves and current loads. By entering the wave and current parameters in table (Tab. 1), linear, nonlinear static and dynamic analysis of the structure can be done under the marine environmental loads.

Table 1. Parameters of wave and current

1	2	3	4	5

KWAVE	KCRC	DEPTH	DENSW	Θw
Z(i)	W(i)	θd(i)		
A(j)	τ(j)	φ(j)		

KWAVE is the options of the wave theory. There are four types of wave loads' theories in ANSYS Program. KWAVE = 0 corresponds the slight wave theory; KWAVE =1 corresponds the Airy wave theory; KWAVE = 2 corresponds the Quintic Stokes Wave theory; KWAVE = 3 corresponds the theory of the wave stream function theory.

KCRC is the option of the wave and current interaction; DEPTH is the depth of water; DENSW is the density of the sea water; θw is the direction of the incident wave; Z (i) is the Z coordinates of the flow of different currents from the seabed to the surface; W (i) and θd (i) are respectively the flow rate and the direction corresponding different heights; A (j), τ (j), φ (j), are respectively the height, the phase angle of peak wave and the cycle time of wave (Fig. 1).

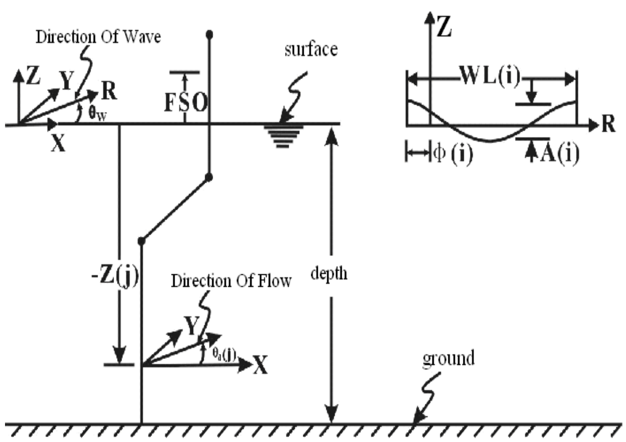

Figure 1. Direction of wave-current

- **COMBIN39 Unit：** COMBIN39 Unit is a non-linear generalized force – deformation axial spring unit. Combined with the force – deformation value under the soil which calculated by p-y curve method, the lateral loads on the pile at each layer of the seabed soil can be simulated**.**

Simplifying the variable-diameter pile. Actually the part of the adjusted diameter is a smooth cone (Figure 2). But the PIPE59 unit does not have the adjustable function, so the pile is simplified to the same diameter pipes whose diameter is increasing along the direction from the top down (Figure 3).

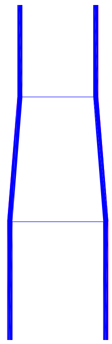

Figure 2. Geometric model

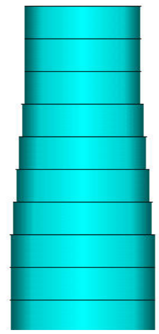

Figure 3. Finite element model

The Choice of Wave Theory. Usually there are 3 types of wave theory: Micro Amplitudes waves, Quadratic Stokes Waves, Quintic Stokes Waves. These theories were formed from certain assumptions and simplifications. As a result of different assumptions and simplifications, not only the results of theoretical calculations but also the scopes of application are different. In this paper, the scope of application proposed by Zhu Yanrong is used (Zhu, 1991). Scopes of application of wave theory are as follows:

- $T\sqrt{g/d} < 6.0, H/d \le 0.2$ Linear Wave theory will be used;
- $T\sqrt{g/d} \le 10.0$ Quintic Stokes Waves theory will be used (Skjelbreia ,1961);
- $T\sqrt{g/d} > 10.0$ Elliptic Cosine Wave theory will be used.

Where: *T*--cycle time of the wave; *d*--water depth; *H*-wave height; *L*--wavelength; *g*--acceleration due to gravity.
According to the above criterions, in this paper, Quintic Stokes Waves theory is used. The options of wave theory can be set KWAVE = 2 in ANSYS program

CALCULATION EXAMPLES

According to the theory above,take a single pile of Chengdao Oilfield Service CB11F platform as an example and analyze wave and current loads.

Structure Type. The pile uses variable-diameter steel pipe of Φ1200 ~ Φ1500. The wall thicknesses of the pipes are 26mm, 30mm, 34mm.The material is the D32.The pile top elevation is 5.0m, the depth of entering into soil is 25m. And there is a 6m × 5m platform installed on the top of the pile.

Environmental Conditions.

- **The normal wave conditions**: The average depth is 12.0m. Tidemark is 1.48m and wave height is 4.75m. The cycle time is 8.6s. The velocity of flow of the surface is 0.96m / s and the velocity of flow of the bottom is 0.71m / s. The wind speed is 28.0m / s.
- **The extreme wave conditions**: The average depth is 12.0m.Tidemark is 3.08m and wave height is 6.45m. The cycle time is 8.6s.The velocity of flow of the

surface is 1.46m / s and the velocity of flow of the bottom 0.94m / s. The wind speed is 30.5m / s.

- **Soil Condition**： The soil conditions of the sea area are listed in Tab.2.

Table 2. Soil Condition

Type Of Soil	Thickness （m）	Effective Density （KN/m3）	Shear Strength （kPa）	Angle of Internal Friction
Silt	2.6	9.7	/	27
Muddy Soil	4.4	7.9	9.7	/
Silty Clay	3.9	8.4	12.8	/
Silt	4.1	10.6	/	23.4
Silty Clay	4.3	9.8	21.1	/
Silt	5.7	10.2	/	27.1
Sandy silt	16.1	10.0	/	30

- **Load Combinations**： According to the way of operating on platform and the principles of load combination, two main typical forms of load combination are considered:
  Normal conditions: The self-weight of live wind load, the wave and current loads and the buoyancy are considered. The direction of Load is along x-axis.
  Extreme wave conditions: The self-weight of wind wave and current loads and the buoyancy are considered. The direction of Load is along x-axis.

Static Analysis. The purpose of static analysis of structures is to obtain the displacement of the top of the pile and the maximum internal force of this component. You can see the results in Table 3.

Table 3. Static Calculation Results

	Normal Conditions		Extreme Wave Conditions	
Type of Piles	Displacement (cm)	Stress (MPa)	Displacement (cm)	Stress (MPa)
Normal Pile	4.47	22.79	11.83	47.11
Variable-diameter Pile	3.46	17.47	8.57	35.55
Decrease	22.6%	23.3%	27.6%	24.5%

Modal Analysis. The basic equation of solving typical non-damping modal is the classical eigenvalue equation:

$$[K]\{\phi_i\} = \omega_i^2 [M]\{\phi_i\} \qquad (3)$$

Note: $[K]$--stiffness matrix; $\{\phi_i\}$--vibration model vector of mode i (eigenvector); ω_i-- natural frequency of mode i(ω_i^2 is the eigenvalue); $[M]$--mass matrix.

Modal analysis is done to the independent pile using Block Lanczos method in ANSYS Program. Natural frequency of each vibration mode will be got and natural cycle time can be calculated. Figure 4 shows the structure's vibration mode diagram of the first three modes.

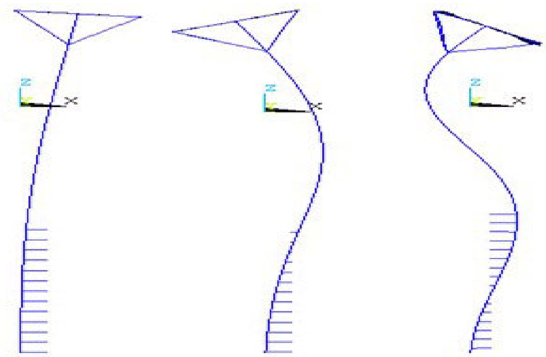

Figure 4. First～Third modes sharp

Among them, the first one shows the transverse vibration.The second shows the vertical vibration, and the third vibration is the direction of torsion. The natural frequencies of first three vibration modes are 1.3133, 7.3887, and 17.748. We can calculate that the first vibration mode's natural cycle time is 0.7s, and the wave cycle time is 8.6s. So the single pile platform's natural frequency keeps different from the waves' frequency to avoid the occurrence of resonance.

Dynamic Analysis. After the transient solution of the independent pile under the wave conditions done by ANSYS Program, the node' horizontal displacement and Time curve can be read from POST26 when the structure's maximum displacement occurres. Figure 5 is the displacement of pile top and time curve in the extreme wave conditions.

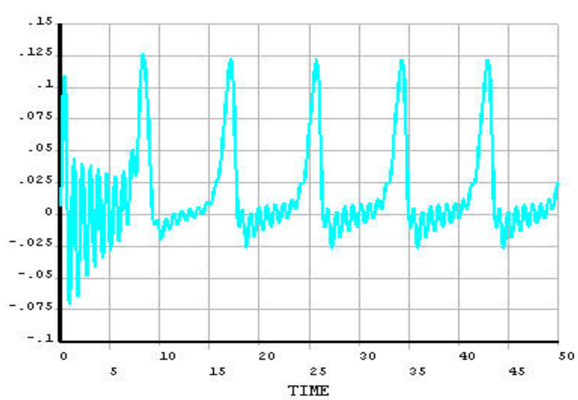

Figure 5. Displacement of pile top and time curve in extreme wave Environment

We can see from Figure 5 that, the maximum displacement of the pile appears when the time is 8.3s. So the maximum displacement and stress at that time can be got through the ANSYS Post-processing Module. The results of these two kinds of piles are listed in Table 4.

Table 4. Comparison between the calculating solutions of the two kinds of piles

	Displacement of the top (cm)			Maximum Stress (MPa)		
Type of Piles	Static	Dynamic	Amplification	Static	Dynamic	Amplification
Normal Pile	11.83	17.57	1.49	47.11	63.17	1.34
Variable-diameter Pile	8.57	12.59	1.47	35.55	47.89	1.35
Decrease (%)	27.6%	28.3%	/	24.5%	24.2%	/

CONCLUSIONS

- When the independent pile is analyzed with the Finite Element Method, p-y Curve Method and Non-linear nature of soil are considered. The anti-force to the pile is simplified as a series of non-linear springs. Pile - soil interaction is truly reflected when we use the element of COMBIN39, that provides new ways of design of the independent piles.
- Comparing the results of the dynamic analysis with the static analysis, we can see that, the dynamic response of pile is more significant under the extreme wave conditions; the amplification coefficient of displacement and stress is greater than 1.3. Therefore, the dynamic response of independent piles must be taken into account.
- Under the extreme wave conditions, either in the static calculation or in the dynamic calculation, displacement and stress of variable-diameter piles are decreased more than 20% compared with the normal pile. So the effectiveness in controlling the shaking and reducing the stress of variable-diameter pile is fully verified.

REFERENCES

API PR 2A: *Recommended Practice for Planning*. Designing and Constructing Fixed Offshore Platform. American Petroleum Institute. (1991)，.

CCS: *Offshore Engineering Rules*. (1992) .China Communications Press, Beijing.

Li, Q. and Yang, S.E.(2003) " The finite element dynamic analysis for self-elevating platform by ANSYS/Multi-physics program." *J. China Offshore Platform*, 18(4), 41~46.

Seventh Conference of Coastal Engineering. (1961). *Fifth Order Gravity Wave Theory. Proceedings*, 1, 184~196, Skjelbreia L and Hendrickson, J.A.

Wang, S. J. and Xu, C. S. (2003). "The developing process of single-well production platform and the developing trend of fixed production platform in Shengli

Oil Field.", *J.China Offshore Platform*, 18(6), 18~21.
Yokoyama Y. (1984) . "Solution and Example of Pile Foundation. Translated by Tang YeqingWu Qingsun." Beijing, 14 -136.
Zang, J.Y. *"The finite element dynamic analysis and study on the reasonable pattern for single pile" M.* Tianjin, Tianjin University, 2005.
Zhu, Y.R. (1991). *"Ocean engineering wave mechanics." M.*Tianjin University Press, Tianjin, 61-62.