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Nonlinear Analysis of Pile Foundation Jacket Platform

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Abstract — In this paper, the nonlinear collapse of the BOHAI−8 pile foundation jacket platform has been analyzed. The ultimate load and collapse process of two computational models of the structure are given. One model is of fixed support whose length is eight times the pile leg diameter and the other considers the nonlinearity of the soil-pile interaction.

Key words: *nonlinear analysis, jacket platform, ultimate load, platform collapse*

1. Introduction

With the development of computer science, the structural design in ocean engineering is not confined to linear analysis, and nonlinear analysis is gradually introduced into the design procedure. Meanwhile, the nonlinear collapse analysis is applied to the platform structure in safety assessment of platforms. Thus, the nonlinear analysis of the jacket platform plays an important role in the ocean engineering.

In the nonlinear analysis, if the load increment given is too small, the whole process of analysis would take a long time. If the load increment given is too large, the equation would not converge in the procedure of equilibrium iteration. In the process of nonlinear analysis of the jacket platform for the maximum load-bearing capacity, usually, large load increment steps are given at the beginning. When some members yield in the jacket structure, the load increment step will be decreased appropriately. With the growth of the yielding members in the structure, the load increment step must be decreased step by step till the jacket structure collapses.

The jacekt platform in ocean engineering is a lattice steel structure. It is a statically indeterminate structure made of main legs, bracing members, deck and pile foundations. Some main legs and bracing members yield first under the environmental load. When the load is continually increased, an increasing number of members will yield till the collapse of the whole jacket structure. According to this characteristic, the main legs and bracing members under the water plane are usually regarded as nonlinear elements and other members as linear elements in the computational model.

In this paper, the nonlinear collapse of the BOHAI−8 pile foundation jacket platform has been analyzed. The ultimate load and collapse process of two computational models of the structure are given. One model is of fixed support whose length is eight times the pile leg diameter and the other considers nonlinearity of the soil-pile interaction.

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2. Computation Method

In the nonlinear analysis, we have computed the response of the finite element system with the increment equilibrium equation solution method. The increment solution method applied is a BFGS (Broyden-Fletcher-Goldforb-Shanno) modified matrix method with the linear searching function. It can finish the finite element method analysis with the geometry and material nonlinear structure (Bathe, 1983).

2.1 Increment Equilibrium Equation of the Finite Element Method

$$ {}^{t}\overline{K}\,\overline{U} = {}^{t+\Delta t}\overline{R} - {}^{t}\overline{F} \tag{1}$$

where

${}^{t}\overline{K}$ — the tangential stiffness matrix at time t;

$\overline{U}$ — the increment of the nodal displacement vector from time t to $t+\Delta t$, i. e. $\overline{U} = {}^{t+\Delta t}\overline{U} - {}^{t}\overline{U}$;

${}^{t+\Delta t}\overline{R}$ — the external load vector on the node at time $t+\Delta t$;

${}^{t}\overline{F}$ — the nodal force vector corresponding to the element stress at time t.

2.2 Iteration Procedure of the Equilibrium Equation

At $t+\Delta t$, the equilibrium iteration is applied with the BFGS method. This iteration procedure is:

$$ {}^{t}\overline{K}^{*}\,\Delta\overline{U}^{(i)} = {}^{t+\Delta t}\overline{R}^{(i-1)} - {}^{t+\Delta t}\overline{F}^{(i-1)} \tag{2}$$

$$ {}^{t+\Delta t}\overline{U}^{(i)} = {}^{t+\Delta t}\overline{U}^{(i-1)} + \beta\Delta\overline{U}^{(i)} \tag{3}$$

in which

${}^{t}\overline{K}^{*}$ — the modified stiffness matrix;

β — the established acceleration factor according to the linear search in the direction of $\Delta\overline{U}^{(i)}$.

2.3 Convergence Criterion

$$ \Delta\overline{U}^{(i)}\left({}^{t+\Delta t}\overline{R}^{(i)} - {}^{t+\Delta t}\overline{F}^{(i)}\right) \leqslant \mathrm{STOL}\ \Delta\overline{U}^{(i)}\left({}^{t+\Delta t}\overline{R}^{(i-1)} - {}^{t+\Delta t}\overline{F}^{(i-1)}\right) \tag{4}$$

where STOL — the allowable value with the convergence.

2.4 Modified Stiffness Matrix Calculation

$$({}^{t+\Delta t}\overline{K}^{*-1})^{(i)} = \overline{A}^{(i)t} - ({}^{t+\Delta t}\overline{K}^{*-1})^{(i-1)}\overline{A}^{(i)} \tag{5}$$

where $\overline{A}^{(i)}$ is an $n \times n$ matrix, i. e.,

$$\overline{A}^{(i)} = \overline{I} + \overline{V}^{(i)}\overline{W}^{(i)t}$$

in which $\overline{I}$ is an $n \times n$ unit matrix. $\overline{V}^{(i)}$ and $\overline{W}^{(i)}$ are obtained through calculation of the nodal force and displacement, i. e.,

$$\overline{V}^{(i)} = -\left[\frac{\overline{\delta}^{(i)t}\,\overline{\nu}^{(i)}}{\overline{\delta}^{(i)t}\,{}^{t+\Delta t}\overline{K}^{*(i-1)}\overline{\delta}^{(i)}}\right]^{1/2} {}^{t+\Delta t}\overline{K}^{*(i-1)}\overline{\delta}^{(i)} - \overline{\nu}^{(i)}$$

$$\overline{W}^{(i)} = \frac{\overline{\delta}^{(i)}}{\overline{\delta}^{(i)t}\,\overline{\nu}^{(i)}}$$

where

$$\overline{\delta}^{(i)} = {}^{t+\Delta t}\overline{U}^{(i)} - {}^{t+\Delta t}\overline{U}^{(i-1)}$$

$$\overline{\nu}^{(i)} = ({}^{t+\Delta t}\overline{R}^{(i-1)} - {}^{t+\Delta t}\overline{F}^{(i-1)}) - ({}^{t+\Delta t}\overline{R}^{(i)} - {}^{t+\Delta t}\overline{F}^{(i)})$$

Eq. (5) is a positive definite and symmetric matrix.

3. Computational Model

The jacket platform in ocean engineering is a lattice steel structure. It is a statically indeterminate structure made of main legs, bracing members, deck and pile foundation. The force is mainly transferred through the bracing members under the environmental load. When the main leg and the bracing member in the jacket platform have yielded, the members above the water plane and the level members are still at the linear stage (Xu and Shen, 1995). So, the main force-bearing members, such as the main leg and bracing members are usually regarded as nonlinear elements and other members as linear elements in our computational model. Compared with the method which considers all the elements of the platform structure as nonlinear elements, this method may not only save a great deal of computer time but also give accurate result of the ultimate structural load.

A definition of the maximum structural load-bearing capacity is: from the theoretical point of view, if a very small load is added after the structure is loaded step by step till a certain value, a large displacement will occur, at this time the structure is unstable, and the load-bearing capacity of the structure reaches the maximum. From the computation analytical point of view, if in the computational method, the control-load is used in the program, the structural load-bearing capacity will be ultimate when a level line in the load-displacement curve appears. If both the control-load and the control-displacement are used in the program, the control-load will be applied first; after the curve of the load-displacement reaches a maximum point, the control-displacement will be applied. At this time, the curve of the structural load-bearing capacity tends to decrease with the displacement increment. It is clear that the structural load-beraing capacity has decreased. The former computational method is applied in this paper.

3.1 Model of the Jacket Platform with the Fixed Pile Leg Support

The computational model of the BOHAI−8 pile foundation jacket platform is simplified, the length of the fixed support under the mud line being eight times the pile leg diameter. The coordinate center is located at the middle point of the platform on the mud line (Fig. 1). The computational model of the jacket structure is divided into 391 nodes and 927 elements where there are 540 beam elements and 387 truss elements. The deck is simplified to a rigid frame. The structure node is considered to be rigid connection. The load on the jacket platform structure includes the dead weight of the platform, the accessory mass of the platform, the dead and live load of the deck, equipment mass, buoyancy, wind load in the X direction of the deck (wind force and moment of force), wave load, ice load, and current.

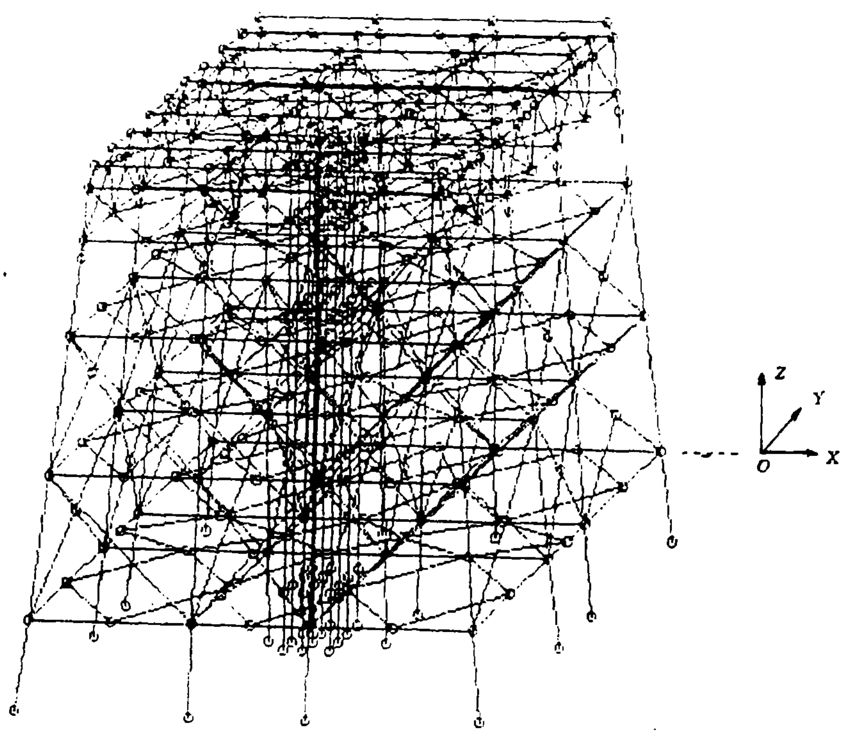

Fig. 1

Both the material nonlinearity (ideal elastic perfectly) and the geometrical nonlinearity (including large displacement and large rotation, but small strain is supposed) have been considered in the nonlinear analysis. The 48 bracing members on vertical pieces (1, 4, 7 and 10) of the jacket platform are regarded as nonlinear elements and other members as linear elements. According to this characteristic of the jacket sructure, large load increment step has been given first in the nonlinear analysis. When the yielding load is approached, the load step is appropriately decreased. The nonlinear elements begin to yield at 6 F_0 (F_0 represents the initial environmental load). As the load step is equal to 9.45 F_0, the structural load-bearing capacity reaches the maximum value (Fig. 2). The 48 bracing members on vertical pieces (1, 4, 7 and 10) of the structure and 16 main legs in the anaysis model are regared as nonlinear elements and other members as linear elements. When the load is equal to 3 F_0, three of 16 main legs begin to yield. As the load is equal to 7.35 F_0, the structural load-bearing capacity reaches the maximum value, and 10 bracing members and all of the 16 main legs yield. If the 16 main legs are regarded as nonlinear elements and other members as linear elements, the ultimate load is equal to 9.0 F_0 (Fig. 2). In Fig. 2, X represents a displacement of a point on the deck and Y is a ratio of the computational load to the initial environmental load F/F_0.

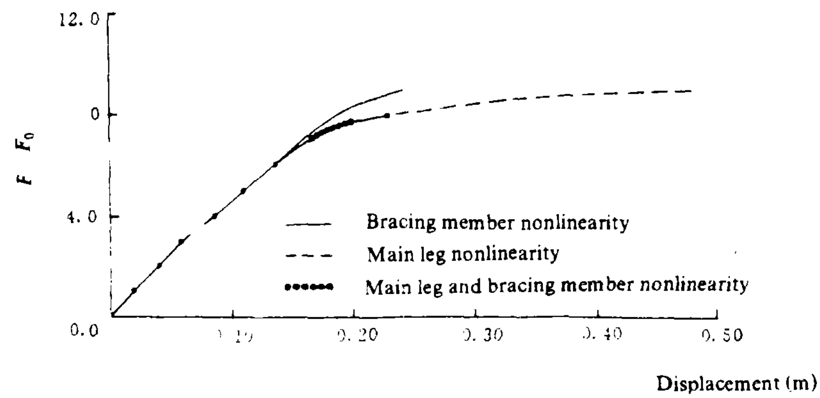

Fig. 2

3.2 Model of the Jacket Platform with Soil-Pile Interaction

The computational model above the mud line is the same as that shown in Fig. 1. The interaction between the soil and pile under the mud line is modeled with the nonlinear spring. The $P-Y$ curve is provided by Bohai Offshore Structural Inspection Company (Table 1). The pile leg of the jacket structure under the mud line is thirty-nine metres in length. According to the $P-Y$ curve, the soil is divided into ten layers. The soil-pile interaction of each soil layer is respectively modeled with the nonlinear spring in the directions of X and Y (Fig. 3). The following three kinds of nonlinear structural models have been calculated:

— 48 bracing members on the vertical pieces (1, 4, 7, and 10) of the jacket platform are regarded as nonlinear elements and other members as the linear elements. The ultimate load is equal to 9.0 F_0 (Fig. 4), where F_0 represents the initial environmental load.

— 16 main legs are regarded as nonlinear elements, and other members as linear elements. The ultimate load is equal to 8.75 F_0 (Fig. 4).

Table 1 $P\text{-}Y$ data

	Depth (m)									
	0.762	1.676	2.591	4.115	5.944	7.620	9.144	11.735	14.783	19.660
Y_1^*	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P_1^{**}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Y_2	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203
P_2	88	193	298	236	693	876	1050	5306	6795	15822
Y_3	0.432	0.432	0.432	0.381	0.432	0.432	0.432	0.432	0.432	0.432
P_3	173	385	595	298	1376	1751	2100	9259	13482	18070
Y_4	0.635	0.635	0.635	0.762	0.635	0.635	0.635	0.635	0.635	0.635
P_4	172	578	945	375	2648	2626	3152	11238	17766	27018
Y_5	0.838	0.838	0.838	1.524	0.838	0.838	0.838	0.838	0.838	0.838
P_5	184	655	1190	473	2528	3502	4308	12894	20396	35900
Y_6	1.067	1.067	1.067	3.048	1.067	1.067	1.067	1.067	1.067	1.067
P_6	194	688	1364	602	2814	4285	5253	14360	22702	39960
Y_7	1.27	1.27	1.27	6.096	1.27	1.27	1.27	1.27	1.27	1.27
P_7	203	717	1421	751	3072	4677	6304	15673	24777	43614
Y_8	1.473	1.473	1.473	7.62	1.473	1.473	1.473	1.473	1.473	1.473
P_8	210	744	1470	809	3306	5036	7022	16878	26680	46964
Y_9	1.70	1.70	1.70	9.525	1.70	1.70	1.70	1.70	1.70	1.70
P_9	217	768	1514	872	3526	5368	7492	17995	28447	50073
Y_{10}	1.905	1.905	1.905	11.43	1.905	1.905	1.905	1.905	1.905	1.905
P_{10}	222	789	1554	926	3734	5680	7928	19042	30102	52985
Y_{11}	2.108	2.108	2.108	13.34	2.108	2.108	2.108	2.108	2.108	2.108
P_{11}	228	809	1590	975	3926	5976	8340	20030	31662	55334
Y_{12}	2.337	2.337	2.337	15.24	2.337	2.337	2.337	2.337	2.337	2.337
P_{12}	233	826	1624	1079	4110	6255	8728	20966	33145	58343
Y_{13}	2.54	2.54	2.54	19.05	2.54	2.54	2.54	2.54	2.54	2.54
P_{13}	238	844	1745	1098	4285	6522	9102	21860	34562	60832
Y_{14}	3.607	3.607	3.607	22.86	3.607	3.607	3.607	3.607	3.607	3.607
P_{14}	261	924	1810	1166	5140	7827	10922	26234	41469	72997
Y_{15}	4.648	4.648	4.648	60.96	4.648	4.648	4.648	4.648	4.648	4.648
P_{15}	284	1006	1964	957	6000	9128	12742	30605	48382	35136
Y_{16}	5.715	5.715	5.715	114.3	5.715	5.715	5.715	5.715	5.715	5.715
P_{16}	308	1087	2116	665	6818	10085	14562	34978	55293	97331
Y_{17}	152.4	152.4	152.4	152.4	152.4	1.542	152.4	152.4	152.4	152.4
P_{17}	308	1087	2116	665	6818	10085	14562	34978	55293	97331

Notes: P^{**} —N / cm; Y^* —cm.

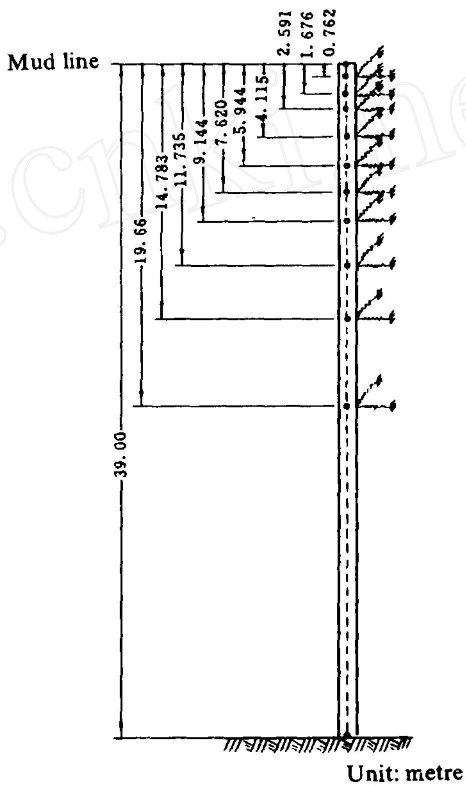

Fig. 3. Soil-pile interaction model.

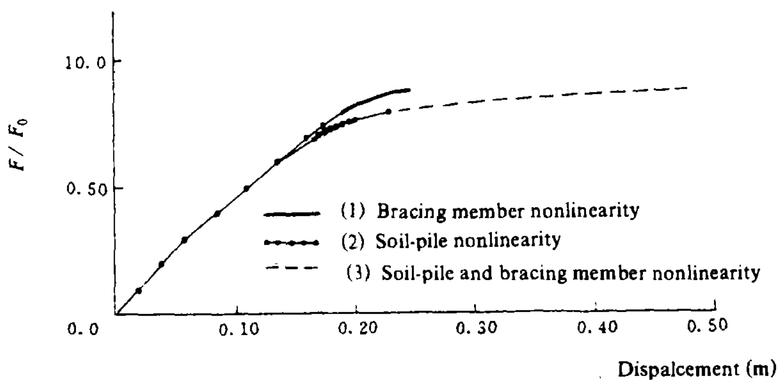

Fig. 4

— 16 main legs and 48 bracing members on vertical pieces (1, 4, 7 and 10) are regarded as nonlinear elements, and other members as linear elements. When the load is equal to 5.0 F_0, some members yield. The ultimate load is 7.7 F_0 (Fig. 4).

4. Conclusion and Discussion

(1) In the fixed support model of the jacket structure, if the main leg or bracing member is considered nonlinear, the ultimate load-bearing capacity of the former is larger than that of the latter. If both are considered to be nonlinear, the ultimate load-bearing capacity is smaller. The reason is that the main leg element and bracing member element alternately yield in the jacket structure.

(2) In the soil-pile nonlinear model, the order of the ultimate load-bearing capacity for the three kinds of the nonlinear structural models is the same as that for the fixed support model.

(3) If both the main leg and bracing member are considered to be nonlinear, the ultimate load-bearing capacity for the fixed support model is smaller than that for the soil-pile model. The safety factor value obtained with the fixed support model is more conservative, thus, it is advantageous to the engineering design department.

(4) The structure discussed in this paper is of universality for the pile foundation jacket platform. The difference lies in the collapse mode due to different directions of the environmental load. As for a jacket platform, if the direction of the environmental load is established, the ultimate load-bearing capacity obtained with the fixed support model is always smaller than that obtained with the soil-pile interaction model.

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