계류돌핀의 말뚝형 하부구조에 대한 실용적 설계 최적화 과정

A Practical Procedure for the Design Optimization of Pile-type Substructure in a Mooring Dolphin

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요 지

계류돌핀의 강관말뚝식 하부구조에 대한 실용적 설계최적화 과정을 제시하고, 수치 예를 통하여 유용성을 평가하였다. 유한차원 최적설계 문제의 정식화에서, 말뚝들을 몇 개의 그룹으로 구분하여 이들의 기하학적 위상과 단면의 치수를 설계변수로 활용하였다. 설계목적함수는 말뚝의 총 중량이며, 설계제약조건은 응력과 근입 깊이, 설계변수의 상한과 하한 등이다. 설계변수의 연계와 고정을 통해 몇 가지의 실용적 설계 대안을 검토하였다. 최적화 프로그램으로는, 순차2차계획법(SQP)을 사용하고 또 쉽게 얻을 수 있는 PLBA 및 IMSL 라이브러리의 DNCONF서브루틴을 이용하였다. 수치예제의 돌핀은 20개의 강관말뚝으로 하부구조를 형성하며, 이중 4개는 연직말뚝이고 16개는 경사말뚝이다. 다양한 대안 설계에서 성공적으로 최적해를 얻었으며, 실용적인 최적 설계과정 임을 확인할 수 있었다.

핵심용어 : 실용설계, 수치적 설계 최적화, 돌핀의 관 말뚝형 하부구조, 설계변수의 연계와 고정, 순차2차계획법

Abstract

In this paper, a practical procedure for the design optimization of tubular-steel-pile-type substructure in a mooring dolphin is investigated and numerically evaluated. In the finite-dimensional optimum design formulation, geometry and cross-sectional shapes of classified group of piles are identified as design variables. The design objective is the total weight of piles, and the design constraints on stresses, penetration depth, and size limits are imposed. Several classes of practical design alternatives are sought through the linking and fixing of design variables. Among the available numerical optimization codes, both PLBA program and DNCONF subroutine in IMSL library are used. They are based on SQP algorithm and relatively easy to get. A dolphin of numerical example has 20 tubular steel piles, 4 vertical and 16 inclined. Optimum designs for different cases are successfully obtained for the practical purpose.

Keywords : *practical design, numerical optimization, tubular-pile-type substructure of dolphin, design variable linking and fixing, SQP algorithm*

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1. Introduction

Dolphin structure can be effectively used for the mooring of VLFS(Very Large Floating Structure)that may cause significant horizontal force. Among the various types of dolphins, pile type mooring system with link connection is advantageously used due to its strength and stiffness sufficient to support horizontal forces.

Recently, a considerable amount of research effort has been made for the design procedure of a steel-pile-type dolphin for the mooring of VLFS, for example 5km×1km, which may be used as an airport or others.[1)]

Mooring dolphin structures of steel pile type are composed of a deck structure(superstructure) and a group of piles(substructure). Deck structure transmits design external forces to the substructure which is composed of a group of vertical and inclined piles.

In this study, a practical procedure for the design optimization of tubular-steel-pile-type substructure in a mooring dolphin is developed and numerically investigated. To formulate the design optimization problem, cross sections and inclination angle of piles are taken as design variables. Design objective is the total weight of steel piles and constraints imposed are of stresses, supporting forces, and the lower and upper bounds on design variables. The aim of this study is firstly to formulate optimum design problem of mooring dolphin of steel pile type in the practical point of view, and secondly to verify the usability and efficiency of numerical design optimization procedure for the practical purpose.

Using the concept of design variable linking and fixing, several class of practically usable design alternatives are sought. Among the numerical tools for finite-dimensional optimization problems, SQP(Sequential Quadratic Programming) algorithms of PLBA(Pshenichny-Lim-Belegundu-Arora) code[2),3)] and NCONF subroutine code in IMSL library are used.

2. Design Requirements of Dolphin Mooring System

2.1 Design Loads

Major loads acting on a mooring dolphin structure are due to wind, wave, current, earthquake, water pressure, berthing and mooring of ship, and the weights of upper deck and facilities. Some of them are presented herein.

Wind force is given in ABS rules,[4)]

$$F_W = 0.0623 C_s C_h U^2 A \tag{1}$$

where C_s=shape coefficient, C_h=height coefficient, U=design wind velocity, and A=projected area in the wind direction.

Wave force can be determined using the modified Morison's formula as the sum of the inertia force F_I and the drag force F_D,[4)]

$$F_p = F_I + F_D = \rho C_m V \frac{du}{dt} + \frac{1}{2} \rho C_d A u|u| \tag{2}$$

where ρ=density of sea water, C_m=inertia coefficient, C_d=drag coefficient, V=volume of structure faced with wave, and u=velocity of water particle.

Current-induced force can be obtained from the drag force term of the modified Morison's formula,[1)]

$$F_C = \frac{1}{2} \rho C_{dc} A V_C | V_C | \tag{3}$$

where C_{dc} is a current-induced drag coefficient, and V_C the maximum current velocity obtained from field observation.

Depending on the size of VLFS and the number of dolphins linked to VLFS, mooring force or berthing force due to ship berth is calculated from the effective berthing energy as,[5)]

$$F_M = C_e C_{vm} C_f C_c \left(\frac{W_s V_s^2}{2g} \right) \tag{4}$$

where W_s=displacement, V_s=berthing velocity, C_e=eccentricity coefficient($\cong 0.5$), C_{vm}=virtual mass coefficient($\cong 1.3$), C_f=flexibility coefficient ($\cong 0.9$), and C_c=coefficient of berth configuration($\cong 0.8 \sim 1.0$). In reality, mooring forces acting on the dolphins are not uniformly distributed as the VLFS deforms elastically. However, the VLFS can be assumed as a rigid body, and consequently, the uniform distribution of design mooring force is resulted.

Mooring dolphin structure in the study has two major structural parts, the superstructure of upper deck and the substructure of a group of tubular steel piles. Since the size of VLFS and the required number of dolphins determine the dimension of the deck structure, the problem of designing substructure is under consideration in this study. Therefore deck structures linked to VLFS just transfer the lateral loads and their own weight to the substructures. Thus, in the design loads for the substructure, vertical loads such as the weight of deck structure and facilities are to be considered with the lateral load carried through links.

2.2 Design Requirements for Substructure

The substructure of dolphin in this study indicates a group of vertical and inclined tubular steel piles supporting the upper deck. The design requirement for the steel piles includes the effect of axial compression and tension forces, lateral(horizontal) forces, and bending moments. According to the allowable stress design method, for example, each design stress in a pile due to the service loads must be smaller than the corresponding allowable stress, and the piles have to be arranged so that they carry nearly-constant loads in the long-term base. For the buckling analysis of a pile, a virtual fixed point is assumed to locate in the specified depth from the surface of the sea bottom. Referring to the virtual fixed point, we also calculate bending moments and axial forces of a pile.

Then, the horizontal reaction F_{iH} on the i^{th} pile is obtained as.[6)]

$$F_{iH} = F_{iw} + F_{iP} + F_{iC} + \frac{1}{n} F_M \tag{5}$$

where F_{iW}, F_{iP}, F_{iC}, and F_M are evaluated for the i^{th} pile using Eqs.(1)-(4), respectively, and n denotes the number of piles in a dolphin.

In the design procedure of tubular steel piles, the design requirement is usually based on axial compression force, axial pulling force, bending moment, combined axial compression and bending, bearing strength, and lateral displacement.

(1) Axial compressive force: Axial compressive force P on a steel pile causes an axial stress σ_c on the effective cross section A_e. It is one of the strength limit states.

$$\sigma_c = P / A_e \tag{6}$$

(2) Axial tension or pull-out force: A pile must be so designed that axial tension force in a pile may not exceed its maximum pull-out force R_{ut}.[1)]

$$R_{ut} = \begin{cases} \frac{1}{5} \overline{N} A_s & \text{for } \textit{sand} \\ \overline{C}_a A_s & \text{for } \textit{clay} \end{cases} \tag{7}$$

where $\overline{N}$=mean of N-values for the total penetration depth of pile, $\overline{C}_a$=mean of adhesive forces for the total penetration depth of pile, and A_s=perimetric surface area of pile.

(3) Bending moment: The design bending stress σ_b in a pile is evaluated using the flexure formula with the design bending moment M and section modulus Z of the pile.

$$\sigma_b = M/Z \tag{8}$$

(4) Combined axial compression and bending: For the case of combined axial compression and bending, the interaction equation must be satisfied.

$$\frac{\sigma_c}{\sigma_{ca}} + \frac{\sigma_b}{\sigma_{ba}} \le 1.0 \tag{9}$$

where σ_c=compressive stress due to axial compressive force, σ_b=compressive stress due to bending moment, and σ_{ca} and σ_{ba} are the allowable compressive stresses.

(5) Bearing strength: Ultimate bearing strength of a pile(Q_u) has 2 components, pile-end bearing force(Q_p) and pile-surface frictional resistance(Q_s) which is again the sum of resistance in sand and clay layers. Due to the pile-end-closed effect, 0.8 Q_p is applied.[6)]

$$\begin{aligned} Q_u &= 0.8Q_p + Q_s = 0.8q_p A_p + f_s A_s \\ &= 0.8(40NL_b/D)A_p + \frac{1}{5}\overline{N}A_{ss} + \overline{C}_a A_{cs} \ge (FS)Q_a \end{aligned} \tag{10}$$

where A_p=cross-sectional area of pile end, N=N-value of soil at pile end, L_b=penetration depth of pile in the seabed, D=outer diameter of pile, $\overline{N}$=mean N-value of sand layer, A_{ss}=surface area of pile penetrated in sand layer, $\overline{C}_a$=mean adhesive forces for clay layer, A_{cs}=surface area of pile penetrated in clay layer, FS=factor of safety, and Q_a=allowable design load

(6) Horizontal displacement: Lateral displacements of the pile top control the horizontal displacement of superstructure. Thus it should be within the allowable limits. The Chang's method may be used to calculate the lateral displacement of pile top.[6)]

$$y_0 = \frac{1+\beta h}{4E\beta^3}T \tag{11}$$

where T=total horizontal load, β=characteristic value in the Chang's Method, h=length of a pile from foundation to top, and EI=flexural rigidity of pile.

3. Design Optimization Problem of Mooring Dolphin

3.1 Formulation

A design optimization problem for the substructure of dolphin can be formulated as a nonlinear programming problem. For the formulation a finite-dimensional vector of design variables is identified, whose components are the diameter and wall thickness of tubular steel piles and the inclination angle of inclined piles. The cost function is defined as the total weight of steel piles, and the constraints of stress, penetration depth, horizontal displacement, lower and upper bounds on design variables are imposed.

Using the allowable stress design procedure, design requirements of Eqs.(6)-(11) are now expressed as the inequality constraints of normalized form.

(1) Constraints for axial compressive stress:

$$\frac{p}{A_e \sigma_{ca}} \le 1.0 \tag{12}$$

(2) Constraints for pull-out resistance:

$$\frac{P}{\frac{1}{5}\overline{N}A_{ss}+\overline{C}_aA_{cs}} \leq 1.0 \qquad (13)$$

(3) Constraints for bending stress:

$$\frac{M}{Z\sigma_{ba}} \leq 1.0 \qquad (14)$$

(4) Constraints for combined interaction:

$$\frac{P}{A_e\sigma_{ca}}+\frac{M}{Z\sigma_{ba}} \leq 1.0 \qquad (15)$$

(5) Constraints for bearing strength:

$$\frac{P(FS)}{0.8(40NL_b/D)A_p+\frac{1}{5}\overline{N}A_{ss}+\overline{C}_aA_{cs}} \leq 1.0 \qquad (16)$$

(6) Constraints for of pile-top displacement:

$$\frac{1+\beta h}{4EI^3\beta}\frac{T}{y_a} \leq 1.0 \qquad (17)$$

(7) Constraints for upper and lower bounds of design variables

3.2 Optimization Method

Mathematical programming methods for a finite-dimensional structural design optimization have in general 3 major steps: structural analysis, design sensitivity analysis, and design optimization.[7] Among the available numerical optimization methods, SQP(sequential quadratic programming) methods are known to be effective.

In this study, the numerical optimization codes of both PLBA(Pshenichny-Lim-Belegundu-Arora) algorithm and IMSL library are used. The PLBA algorithm has the favorable properties of rapid convergence and less number of calculations.[3] The DNCONF subroutine in IMSL library sub- routines also uses an SQP method and it is easy to use in computer centers.

4. Numerical Example

4.1 Description of Mooring Dolphin with 20 Steel Piles

Example dolphin of numerical design optimization has 20 tubular steel piles-4 piles are vertical and 16 piles inclined, as shown in Figs. 1-3. The upper deck(super-structure of dolphin) is assumed to be a plain concrete structure with dimension of 50×16×3m. Tubular steel piles(sub-structure of dolphin) are specified as the SPS 41 of carbon steel in KSD 3566.[6] As shown in the plan view of Fig. 1, upper deck with 4 vertical and 16 inclined piles are symmetrically arrayed with respect to X-and Y-axes. Mean diameter(D) and wall thickness(t) of each pile are the design variables to be determined. Since the horizontal forces(Y-directional forces) from VLFS are thought to be transferred only through the 2 links, the piles are inclined only in the Y-direction. They are shown in Figs. 2 and 3. Profile of pile penetration site is also shown in Fig. 3.

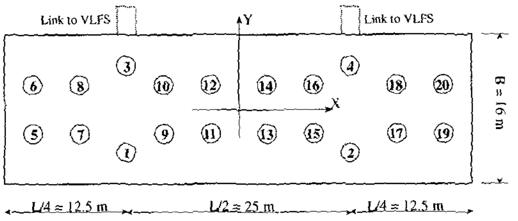

Fig. 1 Plan view and pile array in the upper deck

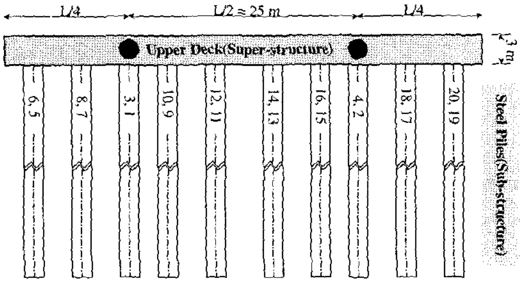

Fig. 2 Y-directional view

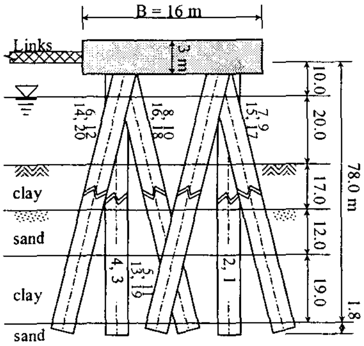

Fig. 3 X-directional view and profile

4.2 Design Variable Linking and Fixing

The cross-sectional dimension of 20 piles, D_i and t_i, $i=1,\cdots 20$, and the inclination angle of 16 inclined piles, θ_i, $i=5,\cdots 20$, are the primary design variables. So, there are 56 design variables. However, the design variable linking and/or fixing is desirable in the practical point of view.[8] Thus, in this numerical example, four classes of design variations are sought through the design variable linking and fixing given in Table 1.

For example, Case 1 in Table 1 has 5 linked design variables - all the vertical piles and the inclined piles respectively have the same cross section and inclination angles are also identical. Moreover, there are only 2 design variables in Case 4 - it assumes all the piles, both vertical and inclined, have the same cross section and the inclination angle of vertical piles is identical and fixed as 20°. So, Cases 1 and 3 are concerned with the design variable linking and Cases 2 and 4 use both linking and fixing.

4.3 Formulation of Numerical Example

Numerical input data for the example problem formulation are presented in Table 2, which are based on the return period of 100 years. The soil properties in the dolphin installation site are also shown in Table 3. They can be used in the calculation of response parameters and formulation of design optimization problem.

External design loads of dolphin are assumed

Table 1 Definition of design variables

Design variable	Case 1	Case 2	Case 3	Case 4
Mean diameter of vertical piles	x_1	x_1	x_1	x_1
Thickness of vertical piles	x_2	x_2	x_2	x_2
Mean diameter of inclined piles	x_3	x_3	linking(=x_1)	Linking(=x_1)
Thickness of inclined piles	x_4	x_4	linking(=x_2)	Linking(=x_2)
Angle of inclination of inclined piles	x_5	fixing(=20°)	x_3	Fixing(=20°)

Table 2 Input data for design formulation

Parameter	Value	Parameter	Value
Current level(C_l)	±2.0m	Wave height(H_{max})	9.2m
Wave period(T)	7sec	Wind velocity(U_{max})	50m/s
Elastic modulus(E)	2.1106kg/cm^2	Current velocity(V_{max})	2.0kt
Unit weight of concrete(γ_c)	2350kg/m^3	Unit weight of pile(γ_s)	7850kg/m^3
Allowable compressive stress(σ_{ca})	As coded	Allowable bending stress(σ_{ba})	1,400kg/cm^2
Sea water density(ρ)	1.03t/m^3	Safety factor(FS)	3.0
Shape coefficient(C_s)	0.5	Drag coefficient(C_d)	0.5
Height coefficient(C_h)	1.0	Inertia coefficient(C_m)	2.0

Table 3 Soil properties of installation site

Depth of layer, m	Soil	Mean N-value	Friction angle	Friction coefficient	Unit weight of soil, t/m^3	Mean Adhesion, t/m^2	Compressive Strength, t/m^2
17.0	clay	-	-	-	1.5	1.39	2.78
12.0	sand	23	34	0.4	2.0	-	-
19.0	clay	5	-	-	1.6	6.0	12.0
1.8	sand	50	37	0.6	2.0	-	-

to act in both X-and Y-direction. The body weight of upper deck(5,640tons) is assumed to be uniformly distributed to steel piles. Design loads due to wind, wave, and current are respectively calculated using Eqs.(1)-(3). However, the mooring forces in the X-and Y-direction are respectively assumed as 300tons and 1,000tons.

The cost function is the total weight of piles. The imposed constraints are on: (1) axial compressive stress of Eq.(12), (2) axial tension or pull-out resistance of Eq.(13), (3) bending stress of Eq.(14) for both X-and Y-direction, (4) interaction relation of Eq.(15) for both X- and Y-directional bending, (5) bearing strength of Eq.(16) for the total layers, and finally (6) upper and lower bounds of design variables ($0.5 \le D \le 5.0$m; $0.0001 \le t \le 1.0m$, $1^\circ \le \theta \le 40^\circ$). The constraints for pile-top displacement of Eq.(17) are not imposed in this example.

4.4 Optimization Program

As the numerical design optimization codes by SQP method, both PLBA and DNCONF subroutine in IMSL library are used. The program PLBA needs 4 user-supplied subroutines to define cost function, constraint function, and the derivatives of cost and constraint functions. Some of the control parameters used in PLBA for the numerical example are penalty parameter(=1.0), rate of active constraint function (=0.1), accuracy of optimum solution(ε_c=0.01), and accuracy of line search(ε_s=0.001).

The DNCONF subroutine also needs user-supplied subroutines to define cost and constraint functions.

4.5 Results and Discussion

The results of design optimization using both PLBA and DNCONF are presented in Table 4. The initial values of the design variables in Table 4 are D=2.0m, t=0.1m, and θ=20°, and cost is 8276ton. Same constraints for upper and lower bound of design variables is used in these results except the Case 1(PLBA), for which the solution failed to converge. So, some of the bounds for Case 1(PLBA) is reduced

Table 4 Design optimizations with PLBA and DNCONF

Design Variable	Case 1		Case 2		Design Variable	Case 3		Case 4	
	PLBA	DNCONF	PLBA	DNCONF		PLBA	DNCONF	PLBA	DNCONF
x_1	3.067	3.629	2.746	4.708	x_1	3.844	3.076	3.804	5.0
x_2	0.020	0.018	0.092	0.020	x_2	0.032	0.034	0.033	0.033
x_3	3.983	3.696	5.0	5.0	$(\equiv x_1)$	-	-	-	-
x_4	0.013	0.018	0.014	0.033	$(\equiv x_2)$	-	-	-	-
x_5	1	1	20.0*	20.0*	x_3	1.451	1	20.0*	20.0*
Iteration	5	25	11	28	Iteration	9	7	11	15
Cost	2149	2669	4265	6364	Cost	4879	4114	5168	6875

for a half of the other cases. The results for Case 1 are obtained and shown in Table 4. When design variables is fixed(Case 2 and 4), the cost is increased. It means that the inclination angle is fixed to 20°, the length of the inclined pile and total weight of the substructure is increased.

In order to confirm the optimum design, the refinements of optimum values are performed. These results are shown in Table 5-8. In Table 5 and 6, the optimization is performed with both PLBA and DNCONF respectively, using the optimum values in Table 4 as initial design. Refined values of Case 3 and 4 in Table 5-6 are equal to optimum value with PLBA and DNCONF in Table 4. And, results of Case1and 2 are almost similar to results in Table 4 except the Case 1(PLBA).

Optimum values with DNCONF and PLBA in Table 4 is also used initial design in Table 7-8,

Table 5 Refinement of optimum values with PLBA

Design Variable	Case 1		Case 2		Design Variable	Case 3		Case 4	
	Initial	Optimum	Initial	Optimum		Initial	Optimum	Initial	Optimum
x_1	3.607	2.697	2.746	2.780	x_1	3.844	3.844	3.804	3.805
x_2	0.020	0.034	0.092	0.093	x_2	0.032	0.032	0.033	0.033
x_3	3.983	4.746	4.999	5.0	$(\equiv x_1)$	-	-	-	-
x_4	0.013	0.007	0.014	0.014	$(\equiv x_2)$	-	-	-	-
x_5	1	1	20.0*	20.0*	x_3	1.452	1.452	20.0*	20.0*
Iteration	5		2		Iteration	2		21	
Cost	2199	1694	4334	4626	Cost	4843	4879	5195	5168

Table 6 Refinement of optimum values with DNCONF

Design Variable	Case 1		Case 2		Design Variable	Case 3		Case 4	
	Initial	Optimum	Initial	Optimum		Initial	Optimum	Initial	Optimum
x_1	3.629	5.0	4.708	3.897	x_1	3.067	3.067	4.5	5.0
x_2	0.018	0.012	0.020	0.019	x_2	0.034	0.034	0.033	0.033
x_3	3.696	5.0	4.999	5.0	$(\equiv x_1)$	-	-	-	-
x_4	0.018	0.013	0.033	0.032	$(\equiv x_2)$	-	-	-	-
x_5	1	1	20.0*	20.0*	x_3	1	1	20.0*	20.0*
Iteration	21		7		Iteration	5		9	
Cost	2609	2492	6270	5894	Cost	4105	4114	6145	6875

Table 7 Refinement of optimum values(DNCONF) with PLBA

Design Variable	Case 1		Case 2		Design Variable	Case 3		Case 4	
	Initial	Optimum	Initial	Optimum		Initial	Optimum	Initial	Optimum
X_1	3.629	2.541	4.708	3.987	x_1	3.067	3.739	4.999	3.092
X_2	0.018	0.020	0.020	0.050	x_2	0.034	0.025	0.033	0.075
X_3	3.696	4.605	4.999	5.0	$(\equiv x_1)$	-	-	-	-
X_4	0.018	0.006	0.033	0.020	$(\equiv x_2)$	-	-	-	-
X_5	1	2	20.0*	20.0*	x_3	1	1.043	20.0*	20.0*
Iteration	7		9		Iteration	2		4	
Cost	2609	1249	6269	4894	Cost	4105	3697	6826	9615

Table 8 Refinement of optimum values(PLBA) with DNCONF

Design Variable	Case 1		Case 2		Design Variable	Case 3		Case 4	
	Initial	Optimum	Initial	Optimum		Initial	Optimum	Initial	Optimum
x_1	3.607	5.0	2.746	3.897	x_1	3.884	4.373	3.804	3.015
x_2	0.020	0.012	0.092	0.019	x_2	0.032	0.022	0.033	0.075
x_3	3.983	5.0	4.9	5.0	$(\equiv x_1)$	-	-	-	-
x_4	0.013	0.012	0.014	0.032	$(\equiv x_2)$	-	-	-	-
x_5	1	1	20.0*	20.0*	x_3	1.451	1	20.0*	20.0*
Iteration	17		9		Iteration	13		7	
Cost	2199	2492	4287	5894	Cost	4893	3763	5195	9402

and PLBA, DNCONF programs are used respectively. These refined values in Table 7 and 8 are similar to the results in Table 5 and 6 respectively. Except Case 4. In Case 4(Table 7 and 8), optimum costs are increased more than initial values. This fact indicate that optimization for Case 4 in Table 7 and 8 doesn't have property of global convergency.

Based on the limited experience of numerical example, several issues may be discussed.[9)] Depending on the codes used, the results of design optimization are slightly different, which may mean that the problem has multiple local optimum design. When the inclination angle is a free design variable(Cases 1 and 3), it tends to converge to the lower bound of the variable. This fact indicates that a dolphin with the vertical piles is effectively applicable in practice. Design variable fixing results in the consistent increase of cost. So, the restrictions in the design space are not generally desirable.

5. Conclusions

Formulation and procedure are presented for a numerical design optimization of mooring dolphin with tubular steel piles. They are formulated and numerically evaluated on the basis of practical point of view. The numerical example of mooring dolphin with 20 vertical and inclined piles is formulated for four design variations based on design variable linking and fixing. For the numerical optimization, both PLBA program and DNCONF subroutine code in IMSL library are used. And optimum designs for different cases are successfully obtained, which can be applied for the mooring of a very large floating structure.

In the study, the practicality and usage of design optimization procedure is emphasized. In practice, the procedure and results may be effectively used to get a preliminary design of a tubular-steel-pile type dolphin.

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