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AN EMPIRICAL DESIGN FORMULA OF A SHARED PILE ANCHOR FOR A FLOATING OFFSHORE WIND TURBINE

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In order to widely promote the large-scale floating offshore wind farm among the private sector, it is the deciding factor how much economical installation method can be developed with regard to the installation cost which accounts for a large proportion in investment costs. In this paper a preliminary design of a shared pile anchor was made based on the result of dynamic mooring simulation and it was found that a simple empirical design formula of an optimum pile specification can be established against N-value, which is useful for preliminary estimation of the installation cost.

Keywords: floating wind turbine, shared pile anchor, empirical design formula, mooring analysis, N-value

INTRODUCTION

In order to widely promote the large-scale floating offshore wind farm among the private sector, it is the deciding factor how much economical installation method can be developed with regard to the installation cost which accounts for a large proportion in investment costs.

The sharing of anchor points by fixed anchors such as pile or suction caisson anchor (Fig. 1, Fig. 2b) clearly reduces cost compared to non-shared anchor (Fig. 2a) However, in terms of installation, since the water depth is deep, there are difficulties of handling multiple mooring chains, and its mechanical behaviors are not well understood.

In this paper, at first simulation considering the interaction between the mooring chain and the seabed is carried out, from which the anchoring force acting on the shared anchor is obtained. Then a preliminary design of a pile is made based on the result, and an empirical design formula relating to the optimum pile dimensions useful for estimation of the installation cost was developed. Finally, a comparison was made for the installation cost of the drag embedment anchor and the shared pile anchor.

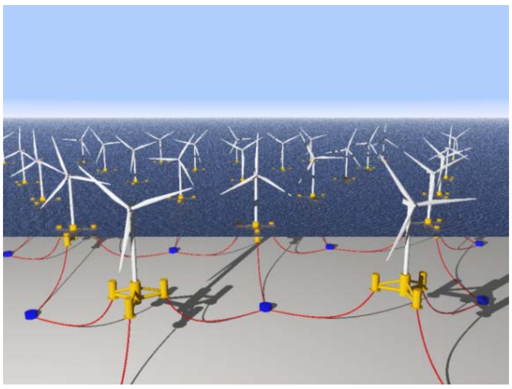
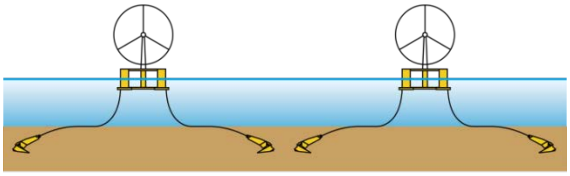
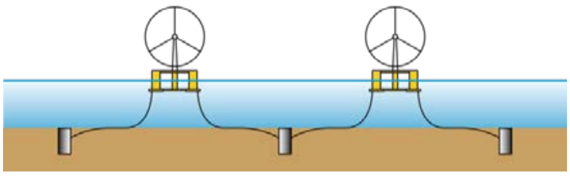


Fig. 1. Schematic view of shared anchor (space among turbines are narrowed for facilitating visualization).



(a)Non-shared anchor (drag embedment anchor)



(b)Shared anchor (pile anchor or suction bucket anchor)
Fig. 2. Anchor for an offshore wind turbine.

ANALYSIS METHOD OF ANCHORING FORCE

The mooring cable acts as a position keeping function and as a restoring force of the floating body. In general, in the floating motion analysis, the main focus is placed on capturing the fluctuation behavior of the floating body, and the mooring is often modeled by a simplified linear spring. However, in this research as it is necessary to calculate the mooring force as accurately as possible, a series of time dependent mooring force simulation [1] based on geometric nonlinear finite element method considering geometric nonlinearity of mooring chains and frictional contact between mooring chain and sea subsurface was performed.

Wind turbine and floater that were analyzed are 2 MW semisubmersible "Mirai" [2] which locates 20 km off the coast of Fukushima prefecture (water depth 120 m). In the analytical models, the wind turbine and the floating body were simplified as a rigid body, but the mooring was modeled by using 40 elastic truss elements / direction × 3 directions=120 elements in which its volume is equivalent to the actual mooring cable. For external force, the wind load and the ocean current load were given as steady load and the regular wave load was given by Morrison equation, in which drag and inertial force coefficients are 0.7 and 1.9, respectively, using linear regular wave of extreme wave height, with extreme load of 50 years of recurrence.

The mooring consists of an R3 type chain with studs (Table 1). The contact between the mooring chain and the seabed surface is modeled by a virtual subgrade reaction spring in the vertical direction and by applying explicitly an external force based on the Coulomb friction using the vertical reaction force at the moment on the mooring cable element in the horizontal direction. The friction coefficient was set to 1.0 according to Ref. [3].

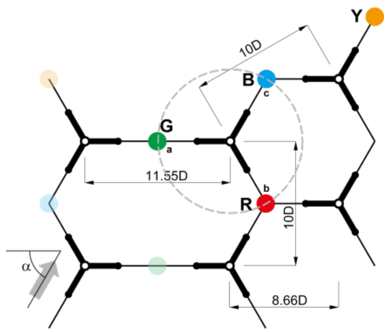


Fig. 3. Layout of wind turbines and anchors.

Table 1 Specification of mooring chain.

Diameter	132 mm
Weight (in water)	331.76 kg/m
Weight (in air)	381.59 kg/m
Stiffness (EA)	156,006 t

Table 2 Metocean conditions.

Wind speed at hub height	50m/s
Significant wave height	11.7m (Extreme wave height : 21m)
Significant wave period	13s
Surface current	1.5m/s
Water depth	120m

Honeycomb arrangement of wind turbine and anchor was assumed (Fig. 3) which is based on a hexagonal module consisting of three or four wind turbines keeping wind turbine spacing of 10D (D: rotor diameter = 80 m) commonly used for an offshore wind turbine to minimize the effect of wake loss. In this situation, four types of anchors are defined, that are, three-direction mooring R, two-direction mooring G and B, and one direction mooring Y. Although six chains are used for mooring in "MIRAI", for sharing of an anchor, in the following, three-direction mooring which unites two chains is used. Irregular wave should be used, however, in order to obtain extreme value wave loads with stable values, enormous computation time is required, so in this study linear regular wave with the maximum wave height of 21 m (significant wave height $H_{1/3}$ = 1.86 times 11.7 m) and period of 13s was used. For the sake of simplicity, wind, wave, and current (Table 2) are assumed to be aligned, and the loading angle is set as shown in Table 3 by considering rotational symmetry.

ANALYSIS OF ANCORING FORCE

Anchoring force characteristics of a single floater

At first, anchoring force characteristics are investigated for a single floater. Fig. 4 shows the expanded shape of the mooring line at the equilibrium position with the loading angle of α = 0° (no wave) with 4 different cable length of L = 450, 460, 470 and 480 m. At L = 450 m it is in tension over almost all of the line. On the other hand, it can be found by the nonlinear contact analysis that as the length of the line becomes longer the tension loosens and the mooring part which contacts with seabed increases.

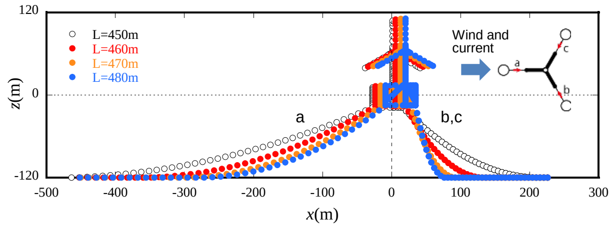


Fig. 4. Finite element analysis of mooring lines at the equilibrium state under steady wind and current loads.

Fig.5 shows tension distribution along the L = 470m mooring lines at the instant of the maximum anchoring force in which wind, wave and current combined loads are applied. Because the mooring lines have initial tension, the tension does not vanish even laying on the seabed.

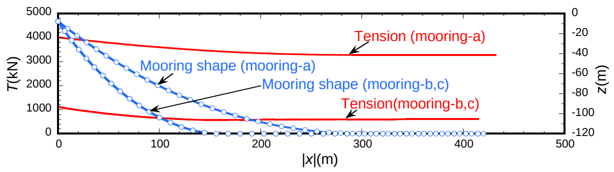


Fig.5. Tension distributions along mooring lines and mooring shapes at the instant of the maximum anchoring force (L=470m).

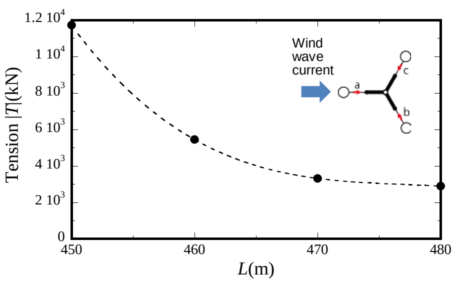


Fig.6. Maximum anchoring force "a" of single floater against length of mooring chain.

Fig. 6 shows the relationship between the mooring length and the maximum tension "a" acting on the anchor when the loading angle α = 0°. When the mooring length is shorter than 470 m, the tension acting on the anchor rapidly increases. If it is too short, the mooring cable becomes taut and a pull out force is generated in the anchor. Therefore, from the viewpoint of anchor design, it is preferable that the mooring cable is as long as possible.

Anchoring force acting on the shared pile anchor

Table 3 summarizes the results of the maximum mooring tension acting on each shared anchor pile for different loading angles in case of a chain length of L=470m. The maximum anchoring force was found on anchor "**G**" when its loading angle was α = 0°. In the following, a preliminary design is carried out against this loading case.

Table 3. Maximum tension (kN) acting on anchors for different loading angles.

Loading angle α	R	G	B	Y
0°	2643	**3310**	3004	1177
30°	—	3049	3113	—
90°	2042	976	1730	988
180°	3078	—	2845	2845
240°	—	2198	—	2605
270°	—	—	2314	2623

EMPIRICAL DESIGN FORMULA OF OPTIMUM SHARED PILE ANCHOR

Assuming ideal uniform sandy soil of constant N-value, pile length$=3/\beta$ (β:characteristic pile length), pile head displacement / pile diameter ≦ 1% and pile thickness / pile diameter ≧ 1.5% by considering the safety margin against buckling when a pile is driven, a relationship between pile diameter and geometrical design values of a pile was obtained for various N-values by Chang's method [4]. Fig. 7 shows a variation of pile thickness, length and weight against pile diameter for N=20 for example. Pile weight becomes the minimum when the pile diameter is 2m. As a result of similar calculations for different N-values from 1 to 50, similarly optimum pile size was found in each N-value as Fig.8.

Fig. 8 also shows the result which takes the reduction of subgrade due to strain into account. Here, according to previous studies [5][6][7][8], reduction of subgrade reaction due to strain was incorporated by Eq. (1) which empirically reduces the subgrade reaction force coefficient according to -1/2 power law,

$$k_h = k_{h0}\Big/\sqrt{\bar{\delta}} \quad (1) \qquad M_{\max p} = \frac{2}{3}H\sqrt{\frac{2H}{3DK_p\gamma'}} \quad (2)$$

where, $\bar{\delta}$: dimensionless pile head displacement$=\delta/\delta_0$, δ : pile head displacement (cm), δ_0 : reference displacement and taken as $\delta_0=1\mathrm{cm}$, k_{h0} and k_h : horizontal subgrade reaction force coefficient at δ_0 according to JRA specification [6] and that takes into account subgrade reduction. Although AIJ guideline [8] takes $\bar{\delta}>0.1$ as a range of application of Eq. (1), here it is taken as $\bar{\delta}>1$ for conservative estimation. The maximum bending moment of an anchor pile was taken as whichever smaller of the maximum bending moment by Chang's method with Eq. (1) and that by Broms's method [9] which is expressed as Eq. (2). Here, H : pile head horizontal applied load, D : pile diameter, and γ' : unit volume weight in water (=8kN/m^3). K_p is the passive earth pressure coefficient, and Coulomb earth pressure was used.

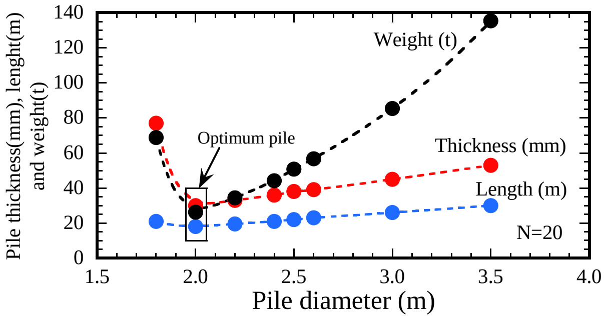
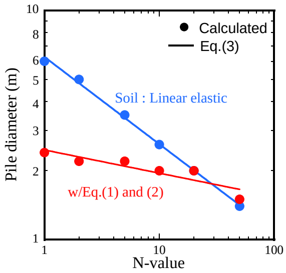
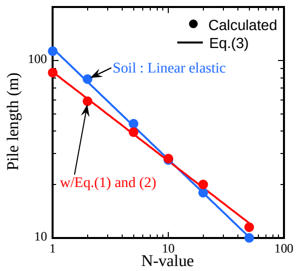


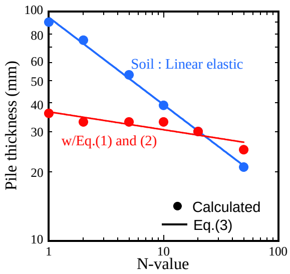
Fig. 7. Variation of weight, thickness and length of the anchor pile against pile diameter (N=20).



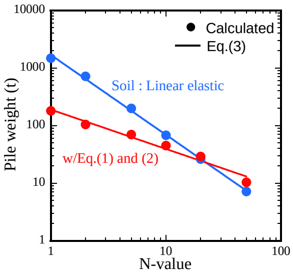
(a) Pile diameter



(b) Pile length



(c) Pile thickness



(d) Pile weight

Fig.8. N-value and dimensions of an optimum anchor pile.

Based on these results, a simple design formula for anchor piles that can be applied in a preliminary design in homogeneous sandy soil sites was developed. The result is expressed by the following formula,

$$y = aN^b \quad (3)$$

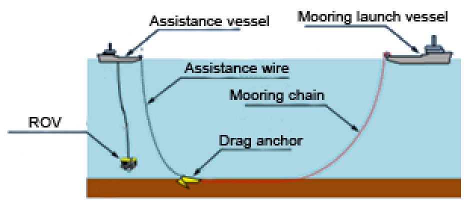
where, y represents the optimum anchor geometrical dimensions, i.e. pile diameter (m), pile length (m), plate thickness (mm) and pile weight (t), and N is the N-value by the standard penetration test of the ground under sea bed. Parameter a and b are shown in Table 4.

Table 4. Parameters of Eq. (3) for optimum pile.

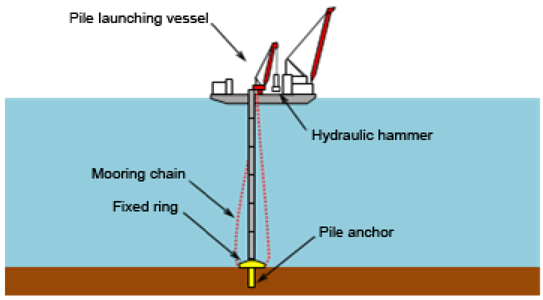
Soil	Linear elastic		Ultimate	
	a	*b*	*a*	*b*
Diameter (m)	6.3	-0.38	2.5	-0.10
Length (m)	117	-0.63	86	-0.50
Thickness (mm)	94	-0.38	37	-0.078
Weight (t)	1689	-1.39	190	-0.68

ESTIMATION OF ANCHOR INSTALLATION COST

In this section, installation cost is compared between conventional drag embedment anchor (Fig.9a) and shared pile anchor (SPA) (Fig.9b). The critical point of selection of SPA installation method is the selection of pile driving method and connection operation of mooring line to anchor, which is operated submerged or in air. For the pile driving, hydraulic hammer (Fig. 9b) and underwater hydraulic hammer can be considered, but the former which is less influenced by the tidal current was adopted. In addition, in mooring line connection, what was adopted was not underwater installation which requires expensive remote control device to handle heavy weight mooring cable, but "in air" installation procedure which fixes the mooring cable to a ring onboard and launches into the water.



(a) Drag embedment anchor



(b) Shared pile anchor

Fig.9. Anchor installing procedures.

For the cost comparison, the following assumptions were made.

(i) As for the oceanic condition at the time of installation operation, the Pacific Ocean offshore which is recognized as being severe worldwide as the wave height is high and the tidal current is fast is assumed.
(ii) As the installation cost of the drag embedment anchor, installation result of the 7 MW offshore wind turbine "Fukushima Shimpuu" which was designed to improve the efficiency of the mooring line installation operation using a winch is referred to.
(iii) A wind farm which consists of 10 floating offshore wind turbines is assumed.
(iv) The parameters of the anchor pile are as shown in Table 5, assuming N = 20 as a standard value of the sandy soil in Eq. (3) (considering the soil nonlinearity).
(v) Steel pipe piles and mooring chains are loaded onto a work vessel at a base port and are transported to the installation site.
(vi) Construction occupancy rate is assumed 50% for both anchors.
(vii) The installation cost is assumed to consist of the installation operation and material that are mooring lines and anchors (steel pipe pile or drag embedment anchor).

Table 5 Shared pile anchor dimensions for installation cost evaluation.

Diameter(m)	Length(m)	Thickness(mm)	Weight(t)
1.9	20	30	25

Table 6 shows the results of estimation of the installation cost. The critical factor that contributed to the reduction of the installation cost of SPA is the reduction of the chartering cost of the work vessel due to the decrease in the number of anchors.

Table 6 Cost evaluation of anchor installation.

	Drag embedment anchor	Shared pile anchor
Cost ratio	1.0	0.6

CONCLUSION

Using the 2 MW floating offshore wind turbine "Fukushima Mirai", optimal specification of piled shared anchor was investigated under the 50-year recurrence storm condition. Also, in consideration of the development of the floating wind farm in the future, a simple design formula that can be applied in preliminary study for uniform sandy soil was developed. As a result of the construction cost examination, it was found that there is a possibility of a reduction of about 40% compared to the cost of the 7 MW floating offshore wind turbine "Fukushima Shimpuu".

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References

[1] P.V. Phuc, T. Ishihara, K. Shimada, and T. Shiroeda, "Dynamic tension analysis of a slack mooring for a floating offshore wind turbine", *Proceedings of RE2014*, 2014.
[2] Fukushima consortium hope page. http://www.fukushima-forward.jp/
[3] DNV-OS-E301, Position mooring, 2013.
[4] Y. L. Chang, Discussion on "Lateral Pile Loading Tests" by L. B. Feagin, *A.S.C.E Transaction*, **102**, pp272-278, 1937.
[5] T. Imai, A study on horizontal K-value (3), K-value adopted in a design, Soil mechanics and foundation engineering, **17**(11) (In Japanese).
[6] Japan Road Association, Specifications for highway bridge Part IV Substructures, 2012.
[7] Japan Road Association, Pile foundation design handbook, 2015 (In Japanese).
[8] Architecture Institute of Japan, Recommendations for design of building foundations, 2001 (In Japanese).
[9] B.B. Broms, Lateral resistance of piles in cohesionless soils, *Journal of the Soil Mechanics and Foundations Division*, *Proc. of the ASCE,* **SM3**, pp123-156, 1964.