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Multi-criteria assessment of offshore wind turbine support structures based on dynamic property optimization①

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Abstract

Increasing size of wind turbine and deep water deployment have raised the issue of appropriate selection of the most suitable support structure to make offshore wind energy cost competitive. The paper presents an optimization methodology for decision making process of bottom mounted supports of offshore wind turbines (OWTs) through reasonable engineering attributes derivation. Mathematic models of support structures are reduced by the generalized single-degree-of-freedom theory with relatively fewer structural parameters. Soft-stiff design optimization based on dynamic properties of OWTs is performed for monopile and lattice supports with different wind turbines, water depth and hub height. Attributes of support structures, wind turbines and environment conditions are applied in the multi-criteria decision making method——TOPSIS for benchmarking of those options. The results illustrate the effectiveness of the proposed optimazation methodology combined with economical and environmental attributes together.

key words: offshore wind turbines (OWTs), support structure, finite element method, generalized single-degree-of-freedom (GSDOF) system, dynamic property, technique for order preference by similarity to ideal solution (TOPSIS) method

0 Introduction

Wind energy industry has moved the interest offshore, taking the advantage of relatively unrestricted space, lower social impact and richer wind resource. A considerable number of offshore wind turbines (OWTs) have been installed in Europe, especially in countries such as Denmark, Sweden, England, Germany, etc.[1,2]. Reference shows offshore wind power will cover 14% of EU's electricity demand by 2030[3]. Interest in offshore wind energy is growing in U. S. and several projects are reaching design stage[4]. Meanwhile, China shows consistent potential for the development of offshore wind energy and some provinces initialized preliminary investigation for offshore wind farms[5].

Increasing size of wind turbines and deep water exploitation is feasible to make offshore wind energy cost competitive, while it will result in huge initial investment for offshore installation is highly sensitive to the weight of components[6]. It is an essential requirement to make support structures of OWTs economic through effective optimization at early design phase. In view of the complexity of socio-economic activities of offshore wind farms, environmental consequence impacts and economic evaluation should be incorporated into decision making for proper support structures of OWTs. Meanwhile, engineering attributes coming from optimization process are fundamental to arrive qualitative and quantitative analysis of enviromental and economic attributes.

Research on optimization mechanism of support structures of OWTs is only at the early stage compared with conventional offshore structures[7,8]. Design processes so far have been based on the experience coming from both wind turbine designers and offshore structure designers[9]. For landed wind farms, rotor-nacelle assemblies and towers are mass produced assuming foundation as fix ends, while it would be sound to take foundation and tower as an integral supporting system subjected to aerodynamic and mechanical loadings from OWT and hydrodynamic marine loadings simultaneously. Besides, the critical requirement of avoiding resonance at turbine rotation frequency restricts optimization goals of support structures[10].

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The paper aims at providing an effective optimazation methodology assessing for a preferable selection of two commonly used support configurations: monopile and lattice with different turbines at various water depth. In this analysis, mathmatic models of monopile and lattice supports of OWTs are constructed by use of the theory of GSDOF system. The optimum technology of support structures based on dynamic properties of OWTs is carried out to make two structures be comparable and arrive reasonable engineering attributes at the same lever. The widely used multi-criteria decision making method——TOPSIS (technique for order preference by similarity to ideal solution) is applied to incorporate multiple attributes into decision making process, considering both quantitative and qualitative criterias[11]. Research results demostrate the comprehensive features of different support with large-MW wind turbine at deeper water. In this analysis, some economic and environmental attributes are referred as Ref. [12].

1 Support structures of OWT

1.1 Support structure configuration

The concept 'support structure' here indicates an entire structure below nacelle, including possible subseabed constructions. It consists of a tower, a transition piece and a foundation together. The configuration of support structures can be categorized into five basic types: gravity, monopile, tripod, lattice and floaters. In view of engineering[13], gravity and monopile structures are commonly used in current offshore wind farms, both suitable for sites with water depth ranging from 0 to 25m. Others are solutions for greater water depth. Tripod designs are well suited for water depth ranging from 20 to 50m and lattice for 20 to 40m. Floating applications are solutions of larger water depth.

Within the scope of this study, two typical configuration of offshore support structures were studied. They are monopile and four-legged lattice structure made of cylindrical steel tubes. Fig. 1 presents a conceptual illustration of two configuration.

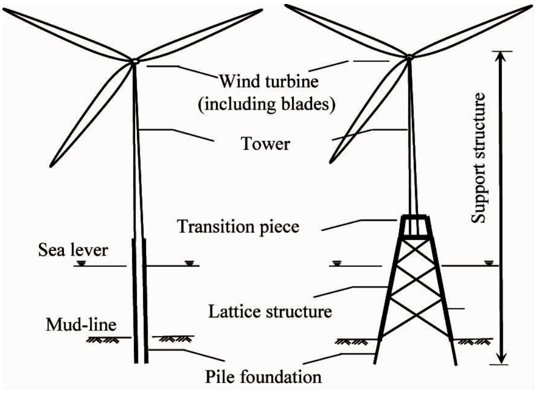

Fig. 1 Monopile and lattice support structures

1.2 GSDOF system of OWT support structure

It is obvious that a classic SDOF system has only a single degree of freedom and the response may be expressed in terms of this single displacement quantity. However, the analysis of most real systems requires use of more complicated idealizations, even when they can be included in the generalized single degree of freedom system freedom (GSDOF) category. The equations of motion and response analysis of complicated structure can be reduced to the form in terms of this single displacement quantity[14]:

$$m^{*}Z''(t)+c^{*}Z'(t)+\bar{k}^{*}Z(t)=p^{*}(t) \tag{1}$$

Applying the procedure of virtual work to GSDOF systems, one obtains the following useful expressions for the contributions to generalized properties:

$$\begin{aligned}
m^{*} &= \int_0^L m(x)\psi(x)^2\mathrm{d}x+\sum m_i\psi_i^2+\sum j_i\psi_i'^2\\
c^{*} &= \int_0^L c(x)\psi(x)^2\mathrm{d}x+a_1\int_0^L EI(x)\psi''(x)^2\mathrm{d}x+\sum c_i\psi_i^2\\
\bar{k}^{*} &= \int_0^L k(x)\psi(x)^2\mathrm{d}x+\int_0^L EI(x)\psi''(x)^2\mathrm{d}x+\sum k_i\psi_i^2\\
&\quad -\int_0^L N(x)\psi'(x)^2\mathrm{d}x\\
p^{*}(t) &= \int_0^L p(x,t)\psi(x)\mathrm{d}x+\sum p_i(t)\psi_i(x)
\end{aligned} \tag{2}$$

where m^{*}, c^{*}, $\bar{k}^{*}$, $p^{*}(t)$ are generalized mass, generalized damping, generalized stiffness and generalized load.

According to the characteristics of support structure, tower of OWT deforms in a single flexural deflection pattern, so simple GSDOF analysis could be made. As an illustration of this method, approximating SDOF behavior in a flexure system actually has infinite degrees of freedom, considering the formulation of an equation of motion for the cantilever tower of Fig. 2.

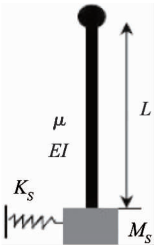

Fig. 2 Support structure treated as a GSDOF system

Taking roter, tower and foundation as a structural system, genralized mass and stiffness of it can be expressed as

$$\begin{aligned} m^{*} &= \int_0^L m(x)\psi(x)^2\mathrm{d}x + M_S\psi(0)^2 + M_O\psi(L)^2 \\ \bar{k}^{*} &= \int_0^L EI(x)\psi''(x)^2\mathrm{d}x + K_S\psi(0)^2 \\ &\quad - \int_0^L M_O g\psi'(x)^2\mathrm{d}x \end{aligned} \tag{3}$$

where $EI(x)$, $m(x)$ are flexural stiffness and mass per unit along the tower; M_S, K_S are equivalent mass and stiffness of foundations; M_O is the total mass of the wind turbine (including rotors) and g is gavity accelaration.

As an illustration of this method approximating SDOF behavior in a flexture system, the support structure's main deform results in tower's deform in flexture. Assuming the vibration of surpport is dominated by his first mode, and the vibration function can be expressed as

$$\varphi(x) = \alpha + (1-\alpha)\left(1-\cos\frac{\pi x}{2L}\right) \quad 0 \leqslant x \leqslant 1 \tag{4}$$

where α is a dimensionless coefficient, which can be interpreted as the relative motion of the foundation to the tower top. From Eq. (4), we get $\varphi(0) = \alpha$ and $\varphi(L) = 1$. Assuming the stiffness and mass along tower are constants, where linear mass density is μ, linear stiffness is EI and substituting the expression into Eq. (3) yields

$$\begin{aligned} m^{*} &= (0.5\alpha^2 + 0.2732\alpha + 0.2268)\mu L + M_S\alpha^2 + M_O \\ \bar{k}^{*} &= (1-\alpha)^2\frac{3.044EI}{L^3} + \alpha^2K_S - (1-\alpha)^2\frac{1.2337M_Og}{L} \end{aligned} \tag{5}$$

from which the value of ω^{*} is found to be

$$\omega^{*} = \sqrt{\frac{(1-\alpha)^2\dfrac{3.044EI}{L^3} + \alpha^2K_S - (1-\alpha)^2\dfrac{1.2337M_Og}{L}}{(0.5\alpha^2 + 0.2732\alpha + 0.2268)\mu L + M_S\alpha^2 + M_O}} \tag{6}$$

In general, α should be between 0 and 1. If the foundation is very stiff, it should have little or no movement, then we have α approach to 0, Eqs (5) (6) become Eqs(7), (8). It can be interpreted as a monopile structure, where the foundation is assumed as fix end.

$$\begin{aligned} m^{*} &= 0.2268\mu L + M_O \\ \bar{k}^{*} &= \frac{3.044EI}{L^3} - \frac{1.2337M_Og}{L} \end{aligned} \tag{7}$$

$$\omega^{*} = \sqrt{\frac{\dfrac{3.044EI}{L^3} - \dfrac{1.2337M_Og}{L}}{0.2268\mu L + M_O}} \tag{8}$$

Neglecting axial force affect, the natural frequency of monopile can be written as Eq. (9), which coincides with Ref. [15].

$$f^2 \cong \frac{3.04}{4\pi^2}\frac{EI}{(M_O + 0.2268\mu L)L^3} \tag{9}$$

If the foundation is very flexible, the stiffness of the tower contribute little to entire structural system. It has a rigid body motion with the foundation, then we have α approach to 1, Eqs(5)(6) become Eqs(10)(11). It can be interpreted as a floating platform of offshore wind turbine.

$$\begin{aligned} m^{*} &= \mu L + M_S + M_O \\ \bar{k}^{*} &= K_S \end{aligned} \tag{10}$$

$$\omega^{*} = \sqrt{\frac{K_S}{\mu L + M_S + M_O}} \tag{11}$$

From the above analysis, the essential physical properties of support structures of OWT could be got by the main parameters of OWT, tower, transition piece and foundation.

1.3 Dynamic property of the OWT support structure

In the OWT structure design, the most visible source of excitation is rotor. It samples the turbulent eddies in the wind field creating peaks in excitation at frequencies of 1P and 3P for a three bladed rotor. Though higher order excitations do occur, here only 1P and 3P are considered as the primary excitations. To avoid resonance, structures should be designed as such that its first natural frequency does not coincide with either 1P or 3P excitation. This leaves possible intervals. A very stiff structure, with its first natural frequency above 3P is called stiff-stiff structure. While a very soft structure with its first natural frequency below 1P is called a soft-soft structure. If the first natural frequency falls between 1P and 3P, the structure is named as soft-stiff shown in Fig. 3.

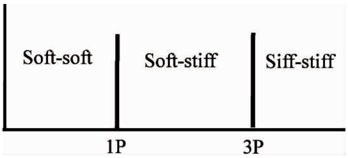

Fig. 3 Frequency intervals of a three bladed constant rotational wind turbine

One of critical design requirement for support structures of OWTs is to avoid resonance at the Np. (i. e. multiples of the turbine rotation frequency) and at the same time avoid resonance with excitation of marine loadings. Since dynamic response contribute a lot to the failure of structure, perfect design would make natural frequency of the support system far away from that of any dynamic excitations. Just like most of fixed platforms of oil & gas farm, they are stiff enough to avoid resonance influence of marine excitations. However, taking both strength and cost into consideration, the natural frequency of the support system of OWT is usually at the same magnitude with the rotation frequency and passing frequencies of blades. For two speed wind turbine, it is confined tightly.

Taking a 1.5MW wind turbine as an example, the monopile support is classified based on dynamic property of OWT. The weight of turbine including blades is around 80t, the hub height is 60m, mean water depth is 10m. According to technical data of the OWT selected, 1P rotational frequency of the three blade turbine is 0.3Hz, and corresponding 3P passing frequency is 0.9Hz. Set allowable avoiding space is 20%, then the natural frequency of the structure should be lower than 0.24Hz for soft-soft design, and larger than 1.08Hz for stiff-stiff design. The range of soft-sitff design is around 0.36Hz ~ 0.72Hz. The steel consumption of above category is listed in Table 1 based on Eq. (9).

Table 1 Material consumption of monopile support

Categary	f_{nat} (Hz)	D (m)	W_{steel} (t)
Soft-soft	0.24	2.44	240.6
Soft -stiff	0.36	3.37	332.3
Stiff-stiff	1.08	8.59	846.9

From Table 1, we can see the frequency of soft-soft design of monopile is closing to the marine wave excitations at around 0.2Hz, while siff-stiff design results in large material consumption. Soft-stiff design scheme is carefully selected based on the research work as one of optimum aims for structures of OWTs in further analysis.

2 Optimization techniques

The optimization design of offshore structures is based on a combination of dynamic properties constrain of OWT and the strength and stiffness provision of structure standards. The design is made place through an iterative process in order to efficiently utilize material properties.

2.1 Finite element models of OWT

The structural models of monopile and lattice supports are built with ANSYS Parametric Design Language (APDL), where design parameters of structural components are carefully defined based on the above analysis for some attributes regarding environmental and economical assessments are derived by the outcome. Main structural parameters used in the analysis are illustrated in Fig. 4.

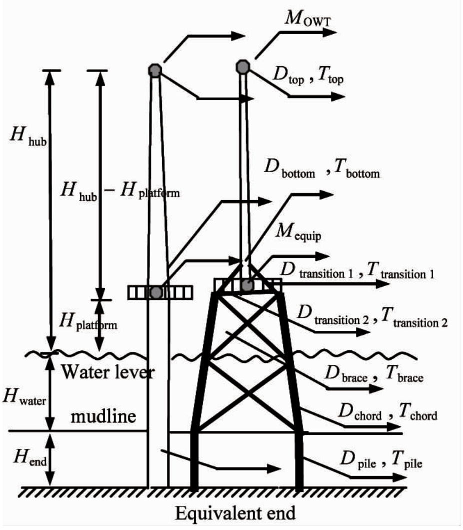

Fig. 4 Optimum design parameters of monopile and lattice support structures

2.2 Design variables

An OWT support structure consists of three sections, which are tower, transition piece and various types of foundation. The design parameters related to optimum solutions can be treated as constant quantity and optimization variables according to feasibilities of projects.

Constants are mainly used in deterministic analysis. For example, once proposed wind farm is sited, the type of OWT and corresponding hub height and top diameter of tower are determined by wind field conditions. Meanwhile, enviromental properties, such as water depth, marine environmental loads, soil properties, etc., can be also treated as constants in hypothetical site of deployment.

Optimal varibles are another kind of design parameters which ensure structural functions with optimum answers. As for supports of OWT studied, such parameters as bottom diameter of tower, wall thickness of tower at top and bottom end, diameter and wall thickness of pile, dimentions of tubular chords of lattice structure, weight of requirement and its placement, are all become optimal variables eventually affecting optimazation results.

Constrain conditions should be set for dimension selection according to engineering feasibilities. For example, taking consideration of relationship of components, bottom diameter of tower should coincide with that of connection componet in transition piece, so do other similar parts. One need to be highlighted here is that the natural frequency of the support structure is constrained as soft - stiff design based on the dynamic properties of OWT.

In short, at preliminary planning state, deterministic quantities and optimazation variables are interchangeable. As for proposed wind farm, supports, OWT types, water depth, hub height can be adjusted to obtain optimal solutions of the whole wind farm.

2.3 State variables

State variables are such kind of structural responses which represent service state of structures. In order to reach the aims of safety, servicability and reliability, state variables should be controlled within requirements of current codes. In this sections, the maximum displacement and Von Mises stresses and dynamic excitation constrains of OWT are selected as state variables of optimazation design.

2.4 Objective functions

Taking full account of engineering characteristics of design variables, overall steel amount of support structures is selected as the objective function discussed under premise state variables. The mathematical model of optimzation problem can be expressed as:

$$\begin{aligned}\min F(X) = F(&M_{owt}, M_{equip}, H_{hun}, H_{platform}, H_{water}, H_{end} \\ &D_{top}, T_{top}, D_{bottom}, T_{bottom}, D_{tansition1}, T_{transition1}, \\ &D_{tansition2}, T_{transition2}, D_{brace}, T_{brace}, D_{chorde}, \\ &T_{chord}, D_{pile}, T_{pile})\end{aligned}$$

$$g(X) \leqslant 0;\ h(X) \leqslant 0$$

$$\begin{aligned}X = [&M_{owt}, M_{equip}, H_{hun}, H_{platform}, H_{water}, H_{end}, D_{top}, T_{top}, \\ &D_{bottom}, T_{bottom}, D_{tansition1}, T_{transition1}, D_{tansition2}, T_{transition2}, \\ &D_{brace}, D_{tansition2}, T_{transition2}, D_{brace}, T_{brace}, D_{chorde}, \\ &T_{chord}, D_{pile}, T_{pile}]^{T}\end{aligned} \tag{12}$$

here, $F(X)$ is the objective function of design variables used to evaluate performance of structures. Optimization solution is the extreme value of the function. $g(X)$, $h(X)$ are restriction conditions of the range of design variable and state variable. Vector X is formed by design variables. A set of vector is a collection of design satisfying specific constrain conditions. Among them, M_{owt}, M_{equip}, H_{hun}, $H_{platform}$, H_{water}, H_{end} can be treated as constant quality in certain hypothetical conditions. Adjusting each of them results in different set of design schemes.

2.5 Optimization results

The basic technical data of OWT used in the support structure optimazation is listed in Table 2. Since the rotor rotation speed is a kind of two speed type, the soft-stiff design scheme for the support structure is confined in a relatively narrow range by dynamic properties of OWT, shown as Fig. 5 and Fig. 6.

Table 2 Technical data of OWT

iterms	3.0MW	5.0MW
Rotor speed (variable)	8.6 ~ 18.4rpm	6.9 ~ 12.1rpm
Rated wind speed	15m/s	13m/s
Weight of OWT (rotor, nacelle included)	111t	410t
Weight of equipment	12t	12t
Displacement of equipment	6m	6m

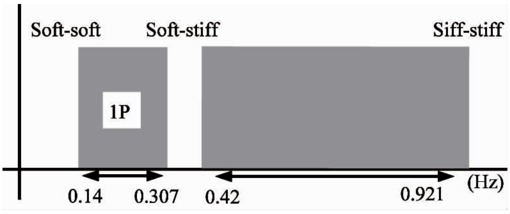

Fig. 5 Frequency ranges of 3.0MW OWT

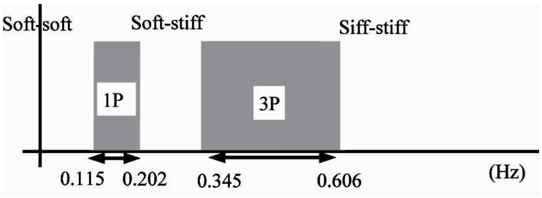

Fig. 6 Frequency ranges of 5.0MW OWT

Combined with the design parameters of OWT and optimazation analysis solutions, the soft-stiff scheme of monopile and lattice support structures with 3.0MW, 5.0MW wind turbines are studied with variations of water depth (10m, 20m, 30m, 40m, 50m) and hub height (60, 70m, 80m, 90m, 100m). Results are compared and demostrated in Fig. 7 and Fig. 8.

Comparing Fig. 7 with Fig. 8, it can be seen that lattice supports are well suitable for relatively deep water, especially when water depth is larger than 30m,

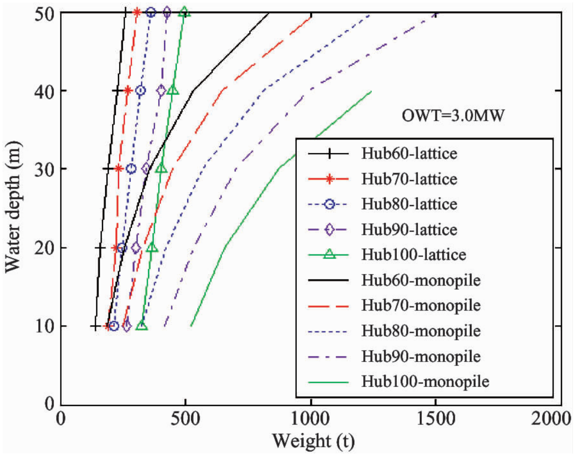

Fig. 7 Weight optimization for support structure with 3.0MW OWT

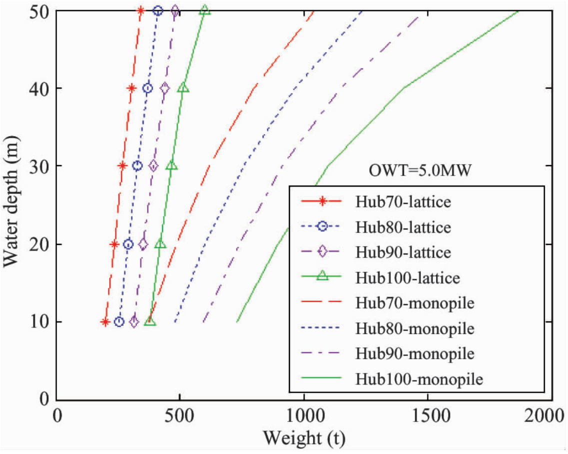

Fig. 8 Weight optimization for support structure with 5.0MW OWT

where large material consumption is needed for the monopile support at the same constrain condition. Moreover, at the same hub height, material consumption is not sensitive with water depth for the lattice support, and the increasing of rated power of OWT does not result in great compensate of material.

3 Multi-criteria decision analysis

Selection of optimum choice of supports should be based on additional attributes more than absolute mechanic aspects. Since the application of multi-MW OWT is an increasing trend for offshore wind energy exploration. 5.0MW OWT at hub height of 100m, the steel consumption of lattice support shows good suitability with variation of water depth in analysis. However, economic or environmenal option may not be the best because of the complexity of socio-economic and biophysical systems. Hence, multi-criteria decision analysis method (MCDA) is employed, which is capable of providing the best alternative in the decision making process, taking conflicting attributes consideration simutaneously.

3.1 Application of TOPSIS method

TOPSIS is selected for it is a powerful MCDA method working satisfactorily in diverse applications[11]. The sequence of this method can be presented as following formulas.

Firstly, it would be the formulation of a design matric

$$X = \begin{bmatrix} X_{11} & X_{21} & \cdots & X_{n1} \\ X_{21} & X_{22} & \cdots & X_{m2} \\ \vdots & \vdots & \ddots & \vdots \\ X_{n1} & X_{n2} & \cdots & X_{mn} \end{bmatrix} \quad (13)$$

where:

X_{ij}: value of the component, which resides in row i and in column j of the X.

i: $1, \cdots, m$, m is the mumber of attributes

j: $1, \cdots, n$, n is the mumber of options

To make different attributes to be comparable, each column vector is normalized as follows:

$$r_{ij} = X_{ij} / \mathrm{sqrt}\Big(\sum_{i=1 \text{ to } m} X_{ij}^2 \Big) \quad (14)$$

r_{ij}: value of the componet, which resides in row i and in column j of the X.

Then, weighted normalized decision matrix v_{ij} is established, where criteria weights w_{ij} indicate their relative importance, and v_{ij} is the product of w_{ij} and r_{ij}:

$$v_{ij} = w_{ij} \times r_{ij} \quad (15)$$

Having obtained v_{ij}, the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) can be expressed as

$$\begin{aligned} A^+ &= (v_1^+, \cdots, v_j^+, \cdots, v_n^+) \\ &= \{ (\max_j v_{ij} \mid j = 1, \cdots, n) \mid i = 1, \cdots, m \} \\ A^- &= (v_1^-, \cdots, v_j^-, \cdots, v_n^-) \\ &= \{ (\min_j v_{ij} \mid j = 1, \cdots, n) \mid i = 1, \cdots, m \} \end{aligned} \quad (16)$$

Since the ideal alternative is arriving when it have the farthest distance from NIS and the shortest distance from PIS. The ranking of it can be calculated by the relative distance of each solution PIS (S_i^+) and to the NIS (S_i^-), shown as

$$\begin{aligned} S_i^+ &= \mathrm{sqrt}\Big(\sum_{j=1 \text{ to } n} (v_j^+ - v_{ij})^2 \Big), \\ S_i^- &= \mathrm{sqrt}\Big(\sum_{j=1 \text{ to } n} (v_j^- - v_{ij})^2 \Big) \end{aligned} \quad (17)$$

Finally, the relative closeness of each option to the ideal C_i will be estimated as follows. The most favourable will be the one closest to 1.

$$C_i = S_i^- / (S_i^+ + S_i^-) \quad (18)$$

3.2 Analysis of attributes

In order to identify the best option of two commonly used support configurations of 5.0MW OWT (hub height 100m) at different water depths (10m, 20m, 30m, 40m, 50m), 10 alternatives (m = 10) and 6 criteria (seen following) have been selected (n = 6) for this problem. The selection is based on the conclusions obtained through the defferent steps of the study and research results given in Ref. [12] for some attributes such as environmental impact economic attributes. All attributes used are defined as follows:

- Artificial reef is a positive parameter, aiming at representing the increment of biodiversity provided by additional substrate for colonization. For this study, it will be assumed that the environmental benefit is proportional to the totoal surface of each structural option.

- Certification is a positive criterion, which shows whether the support has been certified for wind farm or not. Take 1 if it has, 0.5 if not while it has been verified for the same structure used in offshore oil&gas industry and take 0 if it has not. Since monopile and lattice supports have been tested in real wind farms, they are all assumed 1 here which has little influence on the final results and leaves only for a new configuration outlined in the future.

- CO_2 equivalent (CO_2e) is a negative attribute, which reflects the amount of CO_2e emissions produced for the fabrication of different support structures. The amount of CO_2e emissions per kg of steel produced will be calculated by the emissions of N_2O, CH_4 and CO by the following empirical formula:

$$CO_2e = 270 \times N_2O + 24.5 \times CH_4 + 1.4 \times CO \tag{19}$$

For steel members, the unit emissions per kg for N_2O, CH_4 and CO are correspondingly 0.07, 0.04 and 0.93g.

- Depth compatibility is a negative criterion, which demostrates the compatibility of each support option with different water depths. It is scored as 1 if water depth is within the range of reference depth, 2 if it is between 0.75 and 1.25 times of the reference depth, otherwise it is indicated as 3. In the study, it makes 1 for monopile with water depth ranging from 0 to 25m and lattice types with water depth ranging from 20 to 50m. It is considered 2 for monopile support at water depth 30m and 3 when water depth is greater than 30m, the value of which is treated as 3 also for lattice support at shallow water when water depth is assumed as 10m.

- Durability is a positive criterion, indicating the resistance to age deterioration. It is marked with values between 1 and 5, depending on the exposure to corrosion and consequences of fatigue failure. For the lattice support with tubular componet conections, it is treated as 5, and for monopile structure, it is assumed as 4.

- Water turbidity is a negative attribute demonstrating the disturbance to the seabed by support structures. It will be assumed that the environmental impact is proportional to the soil volume affected by piles. The concrete data are calculated from the optimum results.

Based on the above rules and data from optimum results, the initial decision matrix for lattice support structure with 5MW OWT (100m hub height) at water depth changing from 10m to 50m is defined as:

	1	2	3	4	5	6
*M*_10	7.319e5	1	1.5503e7	1	4	2061.8
*M*_20	8.946e5	1	1.8949e7	1	4	2534.5
*M*_30	1.0981e6	1	2.326e7	2	4	3074.5
*M*_40	1.4045e6	1	2.975e7	3	4	3111.8
*M*_50	1.8687e6	1	3.9583e7	3	4	3093.1
*L*_10	3.8167e5	1	8.0845e6	3	5	0.89753
*L*_20	4.2349e5	1	8.9704e6	1	5	0.87836
*L*_30	4.684e5	1	9.9216e6	1	5	0.785
*L*_40	5.1267e5	1	1.0859e7	1	5	0.785
*L*_50	5.7916e5	1	1.2268e7	1	5	5.6441

The normalized decision matrix is derived as:

	1	2	3	4	5	6
*M*_10	0.24197	0.31623	0.24197	0.1857	0.27937	0.32856
*M*_20	0.29576	0.31623	0.29576	0.1857	0.27937	0.40389
*M*_30	0.36303	0.31623	0.36303	0.37139	0.27937	0.48995
*M*_40	0.46434	0.31623	0.46434	0.55709	0.27937	0.49589
*M*_50	0.6178	0.31623	0.6178	0.55709	0.27937	0.49291
*L*_10	0.12618	0.31623	0.12618	0.1857	0.34922	0.000143
*L*_20	0.14001	0.31623	0.14001	0.1857	0.34922	0.000140
*L*_30	0.15486	0.31623	0.15486	0.1857	0.34922	0.000125
*L*_40	0.16949	0.31623	0.15486	0.1857	0.34922	0.000125
*L*_50	0.19147	0.31623	0.19147	0.1857	0.34922	0.000899

The weight vector is based on the experience in this field. Results are referred as Ref. [12] of corresponding attributes:

$$\begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \\ \left[\, 0.65 \right. & 0.65 & 0.91 & 0.91 & 1 & \left. 0.74 \,\right] \end{array}$$

The derived positive and negative ideal solution are derived as:

$$\begin{array}{c} A^+ \\ A^- \end{array} \begin{bmatrix} 0.40157 & 0.20555 & 0.5622 & 0.44881 & 0.34922 & 0.36696 \\ 0.082019 & 0.20555 & 0.11483 & 0.1496 & 0.27937 & 9.257e-5 \end{bmatrix}$$

The relative distance of each solution from PIS to NIS can be calculated as:

$$\begin{array}{c} S^+ \\ S^- \end{array} \begin{bmatrix} 0.53515 & 0.47827 & 0.32932 & 0.18529 & 0.069878 & 0.66094 & 0.71387 & 0.70153 & 0.68954 & 0.67157 \\ 0.075835 & 0.12524 & 0.22392 & 0.36712 & 0.52476 & 0.094402 & 0.0051171 & 0.0059063 & 0.0072238 & 0.01021 \end{bmatrix}$$

The relative closeness of each solution to the ideal C will be estimated as Fig. 9:

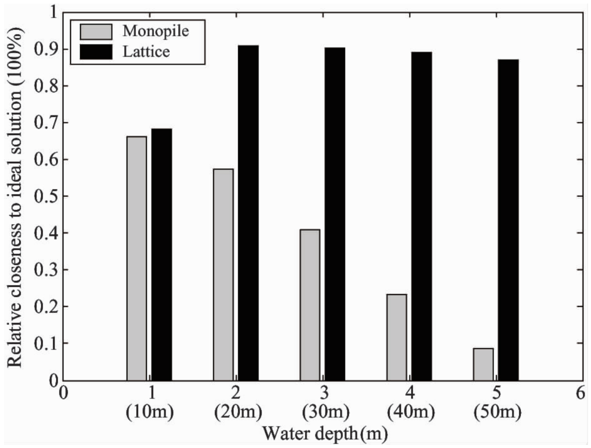

Fig. 9 Ideal C of TOPSIS for support structure with 5.0MW OWT

From the results of the relative closeness of each option to the ideal solution, lattice is found to be the best against monopile and the superiority is getting more obvious as water depth increases.

4 Conclusions

Mathmatic models of monopile and lattice supports of OWTs are constructed by use of the theory of GSDF system. Principal parameters of support structures are brought forward for finite element simulations. Detailed numerical optimization of soft-stiff design scheme is carried on for comparison of monopile and lattice structures with different wind turbine, water depth and hub height. Study shows that lattice structure is an economic drive for multi-MW OWT and deepwater exploitation.

The outcome of above study combined with TOPSIS methods, taking into account additional attributes more than absolute engineering ones, illustrates that for the assumptions considered, lattice support is the best option overall especially when water depth is getting deeper. Since soft-stiff design scheme optimazation adopted by dynamic properties of OWTs fulfills the maximum stress and displacement requirements simultaneously, it could reduce the number of attributes in decision making analysis. This consider is not only an effective methodology used for design scheme evaluation, but also an implementation of the TOPIS method in order to provide an objective methodology for benchmarking different support structure options, taking into account engineering, economic and environmental criteria together.

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