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STRENGTH ANALYSIS OF FIXED STEEL JACKET STRUCTURE UNDER DYNAMIC EFFECTS OF WAVE LOADS IN VIETNAM SEA CONDITIONS

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ABSTRACT: This paper presents an algorithm to evaluate the dynamic effects of wave loads on fixed steel Jacket structures (Jacket structures) through the ratio between the dynamic response and the static response of the structure under the action of sea waves. The algorithm proposed in this paper can be applied to evaluate the dynamic effects of wave loads in the strength analysis for Jacket structures, to provide a limit to the selection of a method for analyzing the structure, and the structure period. The research to find out the limit on the distance between the wave period and the natural period of the structure to choose the appropriate structural analysis method for each sea area is necessary. Because the current Design standards give the “3.0 s or 2.5 s rule”, (use the quasi-static method when $T_{max} \leq 3.0$ s or $T_{max} \leq 2.5$ s) and also only it is clear that the scope of this rule is for the North Sea and the Gulf of Mexico. The research results of this paper will answer the question: Is the use of standards for the North Sea and Gulf of Mexico to analyze Jacket structures in marine conditions outside the study area of the standards suitable? Hoped that this paper will be a reference for engineers when choosing a method of strength analysis of Jacket structures in specific marine conditions at the construction site.

Keywords: Dynamic effects; Wave load; Fixed steel Jacket structure; Strength analysis.

1. INTRODUCTION

Most of the literature acknowledges that the wave spectrum of marine states has a period range from 3 s to 20 s (frequency from 0.33 Hz to 0.05 Hz) [1-3]. Wave loads are dynamic loads by nature, which are roughly described by wave theories or described by the wave spectrum (random waves). In fact, different seas in the world will have different wave parameters as shown in Fig. 1 (for each water depth in different sea areas, the wave height and wave period are different). Wave data to analyze the Jacket structure of different seas in the world will be different. Wave data in some seas around the world are presented in Table 1.

The current standards commonly used to design Jacket structures are usually (API, DNV, ISO, PTS [4-9]). The selection of one or several of the above standards depends on the requirements of the Owner and the technical requirements of the structure.

With the principle that the dynamic effect of the wave load is evaluated when the natural period of the structure is close to the period of the wave. The standards provide a “3.0 s or 2.5 s rule”, using the quasi-static method when $T_{max} \leq 3.0$ s or 2.5 s. This means that the dynamic effect of wave loading only needs to be considered when the natural period of the structure $T_{max} > 3.0$ s or 2.5 s [4-6,9,10]. The standards [4-6,9,10] also indicate the scope of application for each specific sea area, see Table 2.

Monographs and reference books [1-3,12,13]. Here are some excerpts from research related to this article:

- Barltrop, N.D.P.[1] gave the formula to determine the critical value of the specific period of oscillation T_{max} as a basis to take into account the dynamic effect of wave load:

$$T_{\max} = 0.79\sqrt{\frac{d}{g}} \quad \text{(s)} \tag{1}$$

where d is the water depth (m); g is the gravitational acceleration (m/s^2).

Applying Eq. (1) in [1] with a water depth of 20 m to 200 m (water depth in the sea areas where Vietnam is exploiting oil and gas), the results are given in Table 3.

- Wilson, JF [13] examines a linear single degree of freedom structure with a small drag ratio and concludes on the scope of application of quasi-static and dynamic methods, based on the relationship between dynamic effects (DAF) with structural drag coefficient and wave intensity (F_0) and frequency (ω).

Dynamic effects of ocean waves have also been studied and published in recent world journals [14-16,18-22]. These articles all conclude on the dynamic effects of sea waves on each type of structure corresponding to each specific marine condition, as below:

- In 2005, the authors Shehab Mourad and Mohamed Fayed at ICSGE 11 [16], investigated 03 types of Jacket structures with water depths of 90 m, 59 m, and 59.5 m respectively in the North Sea, UK. (H_s = 5.8 m ÷ 16.1 m and T_z = 7.5 s ÷ 11.6 s), using the SACS software program [23] and API-RP2A-WSD-2020 [4] standard. The results of [16] show that the dynamic effect of wave loading in the quasi-static method is smaller than in the dynamic method, this difference is 8% ÷ 25% depending on the type of structure. The effect of marine growth on the dynamic effect of the wave load is quite small, only ≈ 0.25% ÷ 0.7% of the dynamic effect.

- In 1986, S. Walker [15], investigated 02 types of Jacket structures with water depths of 150 m with T_z=3.05 s and 250 m with T_z= 3.47 s respectively in the North Sea, UK. S. Walker recommended that DAF (of single degree of freedom structures) be applied only to structures at water depths from 100 m÷150 m.

- In 1986, Demir I.Karsan [14] evaluated the designs of Jacket structures in the Gulf of Mexico and concluded: Dynamic amplification should be considered when the natural period of the structure is close to the period of the wave load. This dynamic effect is very large when the natural period of the structure is from 6 s ÷ 20 s in the Gulf of Mexico. Therefore, any attempt to reduce the natural period of the structure is associated with concerns about increased structural weight and construction costs.

Applying research results and design standards in the world to Vietnam's sea conditions [24], taking the drag ratio ξ=0.02 and the limit $\Omega = \omega / \omega_1 = 0.75$. The results are presented in Table 4.

The research results from all have the common purpose of choosing a method of evaluating dynamic effects that are closest to reality. Provide advice to evaluate the safety and economic efficiency of Jacket structures subjected to wave action in the specific conditions of each sea area.

The current design standards of Jacket structures in the world are mainly proposed in Europe and America. The European - American standard system is built based on the sea conditions of the North Sea and the Gulf of Mexico. Direct application of European - American standards to design Jacket structures in other sea areas in the world has many shortcomings.

Currently, there are many researches in the world to develop European - American standards for the design and construction of Jacket structures in actual conditions in the seas outside Europe - America.

Table 4 shows that the values of $[T_1]$ are quite scattered ($[T_1]$=1.89 s ÷ 10.35 s). It will be difficult to choose a specific number in Table 4 as a suitable limit for choosing a structural calculation method in Vietnam's sea conditions. It is necessary to study and evaluate the dynamic effects of sea wave loads on the Jacket structure in Vietnam's marine conditions, as a basis for choosing a structural calculation method suitable for Vietnam's sea conditions.

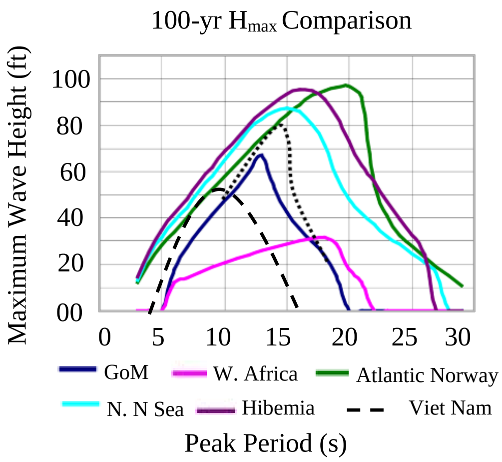

Fig.1 Regional Wave Design Criteria in the world [8] and the South Vietnam sea [11]

Table 1 Wave height and period in some sea areas [8]

Sea area	Location	H_s(m)	T_p(s)
Norwegian Sea	Haltenbanken	16.5	17.0÷19.0
Northern North Sea	Troll field	15.0	15.5÷17.5
North Sea	Greater Ekofisk field	14.0	15.5÷17.0
Mediterranean	Libya	8.5	14.0
	Egypt	12.1	14.4
Gulf of Mexico		11.9	14.2
West Africa	Nigeria	3.6	15.9
	Nigeria	2.7	7.6
	Gabon	2.0	7.0
	Gabon	3.7	15.5
	Ivory Coast	6.0	13.0
	Angola	4.1	16.0
South America	Brazil (Campos Basin)	8.0	13.0
Timor Sea	Non-typhoon	4.8	11.5
Timor Sea	Typhoon	5.5	10.1
South China Sea	Non-typhoon	7.3	11.1
	Typhoon	13.6	15.1

Table 2 Limits of Tmax for using quasi-static methods in standards

Standards	Limit of T_{max} (DAF)	Applicable sea
API	$T_{max} \leq 3.0$ sec	American Sea
ISO	$T_{max} \leq 2.5$ sec ÷ 3.0 sec	North-West Europe Sea; Africa sea; US-Gulf Mexico; Canada Sea
PTS	$T_{max} \leq 2.5$ sec	Petronas
DNV	DAF ≤ 1.1	North-West Europe Sea And refer to ISO
NORSOK	$T_{max} \leq 2.0$ sec ÷ 3.0 sec	Norway Sea
TCVN	DAF ≤ 1.1	Viet Nam Sea

Table 3 Limits to apply quasi-static method or dynamic method to analyze Jacket structure (when applying Eq. (1) in [1])

N^0	Water deep d_o (m)	Limits to applying quasi-static method or dynamic method to calculate Jacket structure T_{max} (sec)
1	20	1.13
2	40	1.60
3	80	2.26
4	100	2.52
5	120	2.76
6	150	3.08
7	200	3.57

Table 4 Limits for choosing structural calculation method (quasi-static method or dynamic method) $[T_1]$ corresponding to Vietnamese sea conditions

Wave direction	Wave period (s)	$[T_1]$ (s)					
		Ω = 0.75	DNV	API	ISO	PTS	NORSOK N003
Repeated wave period 01 year							
N	7.4	5.55	2.22	3	2.5÷3.0	2.5	2.0÷3.0
NE	10.4	7.8	3.12	3	2.5÷3.0	2.5	2.0÷3.0
E	7.8	5.85	2.34	3	2.5÷3.0	2.5	2.0÷3.0
SE	11.9	8.925	3.57	3	2.5÷3.0	2.5	2.0÷3.0
S	11.8	8.85	3.54	3	2.5÷3.0	2.5	2.0÷3.0
SW	7.8	5.85	2.34	3	2.5÷3.0	2.5	2.0÷3.0
W	7.3	5.475	2.19	3	2.5÷3.0	2.5	2.0÷3.0
NW	6.3	4.725	1.89	3	2.5÷3.0	2.5	2.0÷3.0
Repeated wave period 100 year							
N	8.9	6.675	2.67	3	2.5÷3.0	2.5	2.0÷3.0
NE	12.6	9.45	3.78	3	2.5÷3.0	2.5	2.0÷3.0
E	9.4	7.05	2.82	3	2.5÷3.0	2.5	2.0÷3.0
SE	13.8	10.35	4.14	3	2.5÷3.0	2.5	2.0÷3.0
S	13.6	10.2	4.08	3	2.5÷3.0	2.5	2.0÷3.0
SW	9.5	7.125	2.85	3	2.5÷3.0	2.5	2.0÷3.0
W	8.8	6.6	2.64	3	2.5÷3.0	2.5	2.0÷3.0
NW	7.5	5.625	2.25	3	2.5÷3.0	2.5	2.0÷3.0

2. RESEARCH SIGNIFICANCE

Studies and develops an algorithm to evaluate the dynamic effects of wave loads acting on the Jacket structures in strength analysis. Application of the article's algorithm to evaluate the dynamic effect of wave loads when evaluating the durability of some structures of Jacket structures built in Vietnam. Proposes the application limits application of quasi-static and dynamic analysis methods to analyze Jacket structure in Vietnam conditions.

3. DYNAMIC ANALYSIS

3.1 Dynamic Analysis of Jacket Structure

The general dynamics equation of a structure with multi degrees of freedom has the form (2):

$$M\ddot{u} + C\dot{u} + Ku = F(t) \tag{2}$$

where M, C, and K are mass, damping, and stiffness matrices of the structures; F(t) is the load vector; u, $\dot{u}$, $\ddot{u}$ are the displacement, velocity, and acceleration vectors of the structure.

With quasi-static wave load, Eq. (2) will be converted to static calculation form (3) as follows:

$$Ku = F(t) \tag{3}$$

where K is the stiffness matrices of the structures; F is the load vector; u is the displacement vector of the structure.

When using Eq. (3), the dynamic effect of wave loads is taken into account by the dynamic coefficient K_d. The coefficient K_d is determined from the natural period of the structure [1].

Combine Morison wave load (wave load is determined by Morison formula [1,3]) into Eq. (2). The general equation of a linear structure with multi degrees of freedom (2) will have the form Eq. (4) and Eq. (5) as follows:

$$\begin{aligned} M\ddot{u} + C\dot{u} + Ku &= 0.5C_D D_0 \hat{v}.v + \rho C_M A\dot{v} \\ &- \rho C_D D_0 \hat{v}.\dot{u} - \rho(C_M - 1)A\ddot{u} \end{aligned} \tag{4}$$

$$\begin{aligned} &\left(M + \rho(C_M - 1)A\right)\ddot{u} + \left(C + \rho C_D D_0 \hat{v}\right)\dot{u} \\ &+ Ku = 0.5C_D D_0 \hat{v}.v + \rho C_M A\dot{v} \end{aligned} \tag{5}$$

where ρ is the water density; D_0 is the member diameter; A is the member cross-sectional area; C_D is the drag coefficient; C_M is the inertia coefficient; v and $\dot{v}$ are the velocity and acceleration of water flow oriented normally to the axis of the member; $\dot{u}$ and $\ddot{u}$ are the velocity and acceleration of structural displacement; $(v - \dot{u} = r)$ is the relative velocity of water to structure; $(\dot{v} - \ddot{u} = \dot{r})$ is the acceleration of water relative to the structure; $\hat{v}$ is approximated based on the difference of $(|v|.v)$ and $(\hat{v}.v)$ in the sense of "least squared".

Rewrite Eq. (5), we get a new general equation form (6) as follows:

$$M^*\ddot{u} + C^*\dot{u} + K^*u = F^*(t) \tag{6}$$

where $F^*(t)$ is the wave load vector acting on the structure; M^* is the mass matrix of the structure, including the accompanying water volume; $K^* = K$; C^* is the resistance matrix of the structure, taking into account the hydrodynamic drag coefficient of seawater.

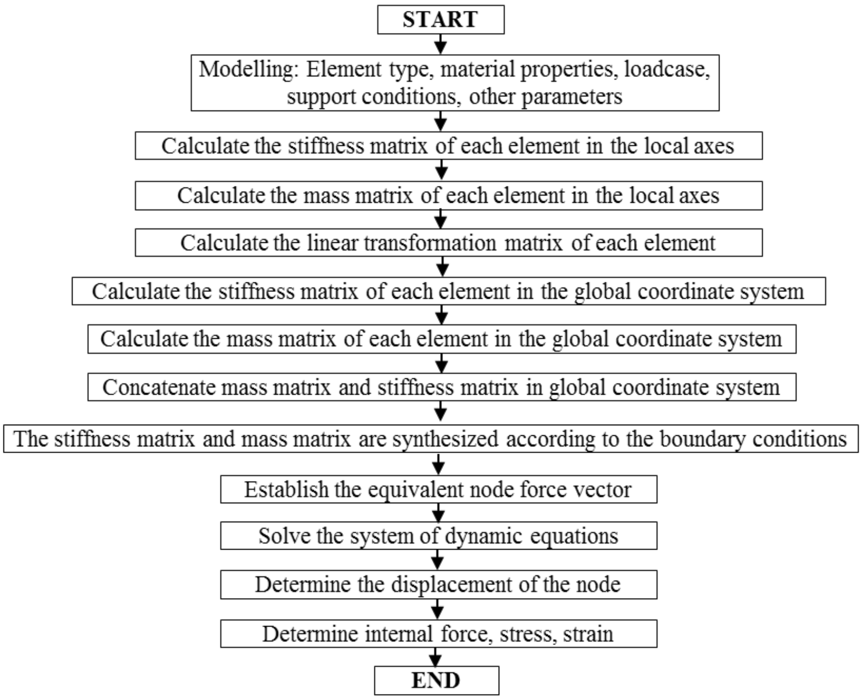

Fig. 2 Algorithm to solve the dynamic equation of the structure by the finite element method

There are many calculation methods to solve Eq. (5) or Eq. (2) presented in [1,3] and [13,25]. This paper will apply the finite element method with a diagram of the main steps to solve the general dynamic Eq. (2), and Eq. (6) shown in Fig. 2.

3.2 Dynamic Effects in Analysis to Check the Strength

3.2.1. Dynamic effects in analysis to check strength, quasi-static method

The general equation in the quasi-static method has the form of Eq. (2). With the wave load as a harmonic function of form $F(t) = F_o \cos \omega t$, from Eq. (2) we can determine the amplitude of oscillation u_o.

$$u_0 = \frac{F_0}{K\sqrt{\left(1-\Omega^2\right)^2 + \left(2\xi\Omega\right)^2}} \tag{7}$$

where K is the stiffness of the structure; Ω is the ratio between the frequency of dynamic load (ω) and natural frequency of structure (ω_1); ξ is the damping ratio; F_0 is the amplitude of load; t is the time. The dynamic effect of the load on the reaction of the structure is assessed based on the comparison between the dynamic response determined from Eq. (2) and the static response determined from Eq. (3). From that, the dynamic effect of wave loads in the quasi-static method (DAF_{QS}) can be determined. DAF_{QS} is evaluated by dynamic amplification factor - DAF (or dynamic coefficient - K_d) as follows:

$$DAF_{QS} = K_d = \frac{1}{\sqrt{\left(1-\Omega^2\right)^2 + \left(2\xi\Omega\right)^2}} \tag{8}$$

3.2.2. Dynamic effects in analysis to check strength, dynamic methods

The general dynamics and statics equations of multi degrees of freedom structures have the form (2) and (3). The dynamic effect of the multi-degree of freedom structure is evaluated based on the dynamic response determined from Eq. (2) compared with the static response determined from Eq. (3).

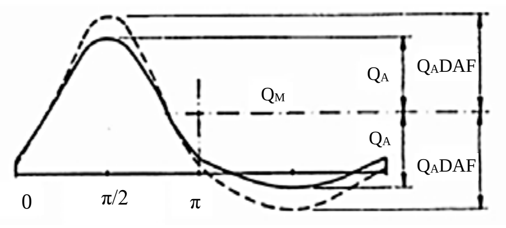

Fig. 3 Dynamic effects corrected by base shear

Dynamic reactions include (horizontal displacement, total shear force, stress, ...) [1,9]. This paper evaluates the dynamic effects in general as follows:

$$DAF_D = \frac{\text{Maximum base shear in dynamic response}}{\text{Maximum base shear in static response}} \quad (9)$$

3.2.3. Algorithm diagram for dynamic effect evaluation

Diagram Fig. 4, combined with the algorithm of SACS software [32], we build a general schematic diagram for strength analysis and fatigue analysis based on quasi-static and dynamic methods as shown in Fig. 5.

Branch A of the diagram Fig. 5 is an algorithm for strength analysis, with the main blocks as follows:

(1) Block **A1.1**: Determination of wave load at operating conditions (one-year repeating period wave);

(2) Block **A1.2**: Determination of wave load with extreme storm conditions (100-year repetition wave);

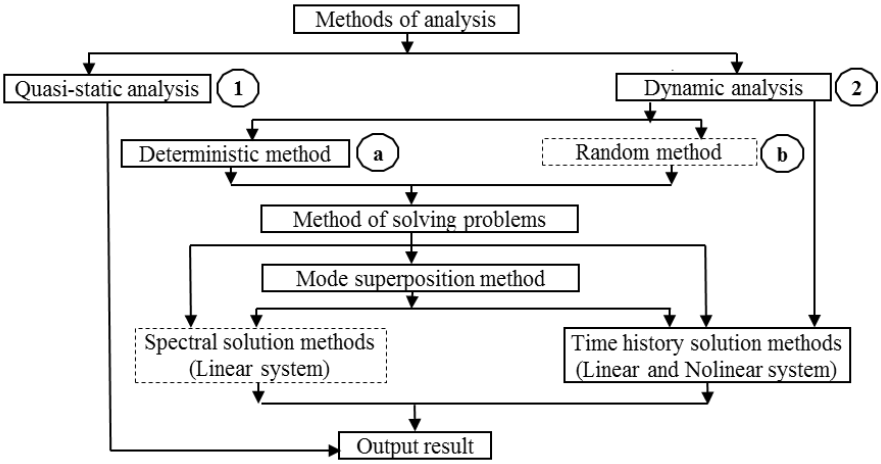

Fig. 4 General schematic diagram for analysis methods

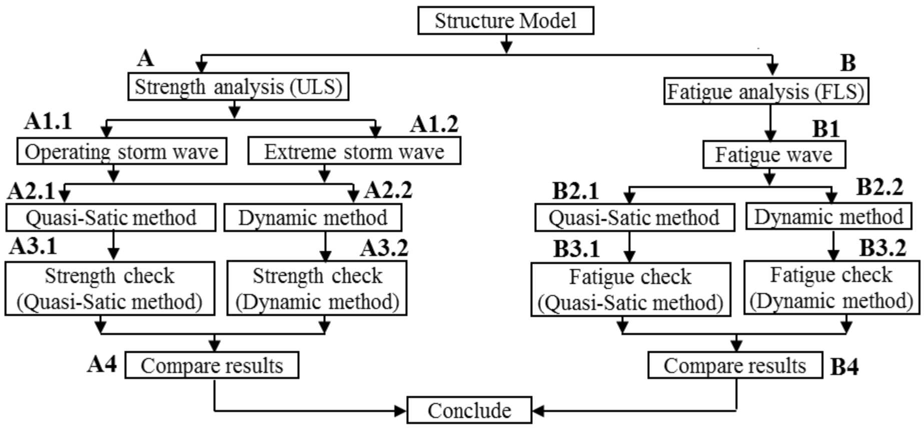

Fig. 5 General schematic diagram for strength analysis and fatigue analysis based on quasi-static and dynamic methods

(3) Block **A2.1**: Calculating the structure by quasi-static method (see detailed algorithm diagram Fig. 6);

(4) Block **A2.2**: Calculating the structure by dynamic method (see detailed algorithm diagram Fig. 8);

(5) Block **A3.1**: Streng checking of bars and buttons through UC, with internal force results at block A2.1;

(6) Block **A3.2**: Streng checking of bars and buttons through UC, with internal force results at block A2.2;

(7) Block **A4**: Compare the results from A3.1 and A3.2 and evaluate the results through the values of the material utilization factor UC: (UC_{QS}, UC_D).

Fig. 6 shows the algorithm of the quasi-static method and the dynamic deterministic method for strength analysis, specifically including the following blocks:

- The quasi-static method, Block A2.1:

(1) Block **A2.1.1**: Modeling Jacket structure: modeling elements, nodal connections, materials, loads (including the mass of materials, equipment, marine growth, and accompanying water) and associated with the background (boundary conditions), …;

(2) Block **A2.1.2**: Calculate the natural period of the Jacket structure according to the calculation diagram modeled in block A2.1.1;

(3) Block **A2.1.3**: Determine the dynamic coefficient DAF_{QS} (dynamic effect with the quasi-static model, Eq. (8)) for each wave direction corresponding to operating conditions and extreme storm conditions;

(4) Block **A2.1.4**: Structural analysis with load combinations (including DAF_{QS} dynamic coefficient, which is the result in block A2.1.3). Durability test (determining the material utilization factor UC) of the bars and buttons of the Jacket structure;

(5) Block **A2.1.5**: After checking the structural strength of the Jacket structure, if the values UC > 1, it will return to adjust the Jacket structure model in block A2.1.1. The calculation process will end when all bars and nodes have UC < 1.

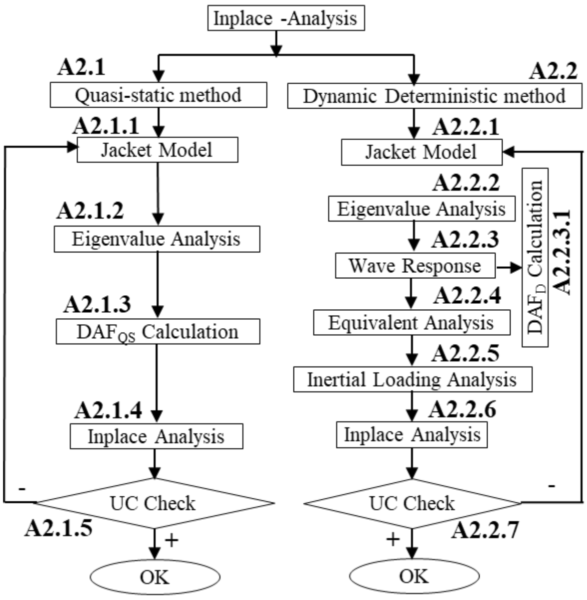

Fig. 6 Schematic diagram for strength analysis

- The dynamic deterministic method, Block A2.2

(1) Block **A2.2.1**: Modeling Jacket structure: modeling elements, nodal connections, materials, loads (including the mass of materials, equipment, marine growth, and accompanying water) and associated with the background (boundary conditions), …;

(2) Block **A2.2.2**: Calculate the natural period of the Jacket structure according to the calculation diagram modeled in block **A2.2.1**;

(3) Block **A2.2.3**: Determination of dynamic response of wave loads by mode analysis for each wave direction corresponding to operating conditions and extreme storm conditions;

(4) Block **A2.2.3.1**: The result of block **A2.2.3** determines the total dynamic bottom shear force and the total static bottom shear force. Determine the dynamic coefficient DAF_D (dynamic effect with a dynamic model, Eq. (9)) for each wave direction corresponding to operating conditions and extreme storm conditions;

(5) Block **A2.2.4**: Perform equivalence analysis from the dynamic response of wave load in block **A2.2.3**;

(6) Block **A2.2.5**: From the results of the equivalent analysis in block **A2.2.4**, determine the inertia force due to the vibration of the structure due to the action of sea waves;

(7) Block **A2.2.6**: Structural analysis with load combinations including inertia forces in block **A2.2.5**. Durability test (determining the material utilization factor UC) of the bars and buttons of the Jacket structure;

(8) Block **A2.2.7**: After checking the structural strength of the Jacket structure, if the values UC > 1, it will return to adjust the Jacket structure model in block **A2.2.1**. The calculation process will end when all bars and nodes have UC < 1.

4. ASSESSMENT OF DYNAMIC EFFECTS

Assessing the dynamic effects of wave loads in the analysis of the fixed steel offshore structures for a specific sea condition, we need to consider the key elements: the natural period of the structure; wave period; damping ratio; marine growth.

Through the typical structure of Jackets that have been built in Vietnam in the past, from which some typical Jackets will be developed to assess the dynamic effect of wave load on the fixed steel offshore structures when building in waters from shallow water to deep water for Vietnam's sea conditions.

4.1 Relation of Water Depth and Dynamic Effect

Assuming T is constant for a given sea condition, we consider the change of T_1 when the water depth of the Jacket increases gradually through a simple structure form equivalent to a single degree of freedom.

$$T_{\max} = T_1 = 2\pi\sqrt{\frac{M}{K}} = 2\pi\sqrt{\frac{ML^3}{3EI}} \tag{10}$$

Through Eq. (10), it is found that when the water depth of the structure increases, the value of L increases (in addition to the weight M also increases), therefore the value of T_1 increases, so the ratio $\Omega = T_1 / T$ in Eq. (8) increases. If L continues to increase, the ratio Ω increases close to the value of 1, this time the dynamic effect K_d will increase significantly.

4.2 Relation of Damping Ratio and Dynamic Effect

For a structure of a single degree of freedom, the damping ratio in Eq. (8) is determined as follows:

$$\xi = \frac{C}{C_{cr}} = \frac{C}{2\sqrt{KM}} \tag{11}$$

where C is the coefficient of damping; C_{cr} is the coefficient of critical damping.

The total damping coefficient C, includes structural damping, hydrodynamic damping, and soil damping. The structural damping depends on the design. Typical structural damping is expected to be 1% ÷ 3%. The soil damping depends on piles design and bottom conditions which means that the soil damping will depend on the design and construction location. Typical soil damping is expected to be 0% ÷ 2%. The hydrodynamic damping depends on leg structure, drag coefficients, and relative water particle velocity. This means that hydrodynamic damping is not only design dependent, but it also depends on sea conditions and marine growth. Typical hydrodynamic damping is expected to be 2% ÷ 4%. According to current standards, the total damping ratio ξ for Jacket structures is usually from 2% ÷ 5%.

The natural period of structure with damping, T_c, is determined as follows:

$$T_c = 2\pi\sqrt{\frac{M}{K\left(1-\xi^2\right)}} \tag{12}$$

Through the calculation example, we found that for structure with small damping (from 2% ÷ 10%), the natural frequency of the structure damping (ω_c) is almost equal to the natural frequency of the structure without damping (ω), with damping ratio ξ = 10% then ωc = 99,50% ω.

4.3 Relation of Marine Growth and Dynamic Effect

Different seas have different environmental conditions, so the development of marine life is different, so the marine growth for the seas is different.

Issues of the effect of marine growth on Jacket structures should be considered when assessing the dynamic effect of wave loads impacting on the fixed steel offshore structures, including:

(1) Increase in structural weight

(2) Alteration of the natural frequencies

The increase in displaced volume due to the presence of marine growth will increase the mass, M_r, and hydrodynamic added mass, M_a. These increases in mass will increase the natural frequency of the structure, see Eq. (12) below:

$$T_1 = 2\pi\sqrt{\frac{M}{K}} = 2\pi\sqrt{\frac{M_r+M_a}{K}} = 2\pi\sqrt{\frac{(M_r+M_a)L^3}{EI}} \tag{13}$$

Therefore, according to the formula (8), an increase in T_1 leads to an increase in the dynamic effect K_d.

(3) Increase in wave loading

- Increasing wave load due to increasing column diameter: An increase in marine growth will increase the diameter.
- Increasing wave load due to increased surface roughness: this increase in surface roughness will change the hydrodynamic coefficient (C_D is drag coefficient, C_M is inertia coefficient).

(4) Increase in flow instability

Table 5 is the thickness of marine growth on Jacket structures used as input to evaluate the dynamic effect under Vietnamese conditions.

Table 5 The thickness of marine growth on Jacket structures used as input to evaluate the dynamic effect under Vietnamese conditions [24,26]

Water deep (m) from MSL	The thickness of marine growth (mm)
MSL	51.0
-4.60	153.0
-48.80	102.0
Seabed elevation	25.0

4.4 Comment and Choose Parameters for Analytical Calculations

Through specific analysis of a simple structure according to form of a single degree of freedom above, it is found that the natural period of the structure (T_1), the wave period (T), and the damping ratio ξ, marine growth affect the assessment of dynamic effects of wave load on Jacket structure. In particular, water depth is one of the important parameters related to assessing the dynamic effect of wave load on Jacket structure.

For this study, given the specific sea conditions in Vietnam, to assess the dynamic effect of wave load on Jacket structure when constructing from shallow water to deep water, we choose the parameters of damping ratio, marine growth, and hydrodynamic coefficient as follows:

- Damping ratio ξ = 2% for strength and fatigue analysis.
- Marine growth on a Jacket structure: drag coefficient C_D = 1.05, inertia coefficient C_M = 1.2 for strength analysis.
- The data on the thickness of the marine growth with the Southern sea conditions of Vietnam.

4.5 Characteristics of Jacket Structure in Vietnam

Jacket structure in Vietnam today most of the typical shape is a truncated pyramid of 4 legs, 8 legs, and 12 legs, the number of diaphragms from 3 ÷ 6, piles are inserted in the legs or using skirt piles, the water depth is from 30 m ÷ 130 m, the material is steel according to API 5L standards or equivalent.

Through the statistical table of the main technical parameters (type of Jacket; the number of the diagram; the number of piles; water depth; natural period) of 82 Jacket structures recently (up to 9/2017), we built the relationship graph between the water depth d_0 and the natural period T_1 of Jacket structure built in Vietnam, Fig. 7.

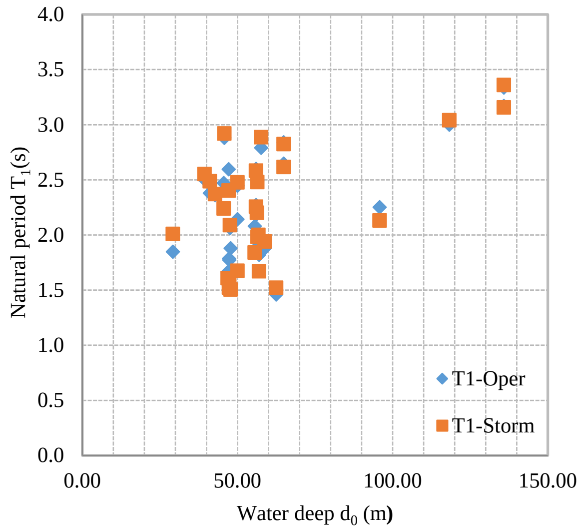

Fig. 7 The relationship graph between the water depth d_0 and the natural period T_1 of the Jacket structure built in Vietnam

4.6 Main Parameters of Jacket for Assessment of Dynamic Effects

To clarify the dynamic effect of wave load on Jacket structure corresponding to Vietnam sea conditions when building from shallow water to deep water area, we calculate and survey the dynamic effect with 03 Jacket structures at water depths 65 m, 90 m, and 120 m. The main parameters of 03 Jacket structures are shown in Fig. 8 and Table 6.

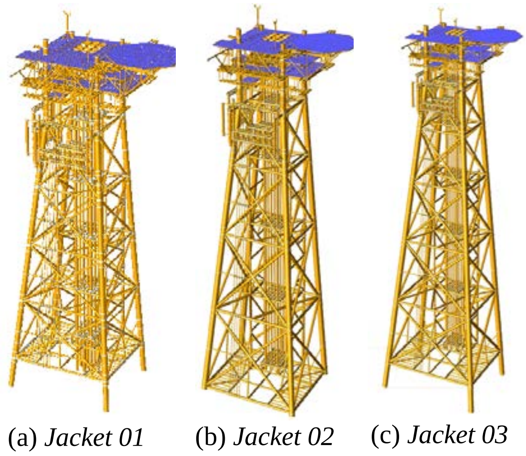

Fig. 8 Structural diagrams of Jackets used to perform survey calculation

Table 6 Main parameters of Jacket for analytical calculations

Main parameters	Jacket 01	Jacket 02	Jacket 03
Water depth do (m)	65	90	120
Topside (m)	24×28	24×28	24×28
No. of legs	4	4	4
No. of diaphragms	4	5	6
Legs (mm)	1650×25	1965×30	2290×40
Topside weight (T)	1680.3	1680.3	1680.3
Jacket weight (T)	3526.4	4951.9	7804.8
T_1 - Operating (s)	2.144	2.800	3.287
T_1 - Storm (s)	2.110	2.775	3.266

4.7 Wave Parameters for Assessment of Dynamic Effects

Wave data were taken from oil and gas exploration site lot numbers 01/97 and 02/97 of the Southern sea of Vietnam [24, 26]. According to [3, 20], the wave parameters for durability test calculation are listed in Table 7.

4.8 Software and Standards for Analysis

Software used in the computational analysis is SACS software [23].

The standard applied in the computational analysis is the API RP2A-WSD 2000 [4].

Table 7 The wave parameters for strength analysis

Wave direction	Direction (degree)	H_{max} (m)	T_{max} (s)	H_s (m)	T_p (s)
		Wave parameters			
Repeated wave period 01 year					
N	225^O	4.7	7.4	2.5	7.4
NE	180^O	9.9	10.4	5.3	10.4
E	135^O	5.2	7.8	2.8	7.7
SE	90^O	4.0	11.9	2.1	11.9
S	45^O	3.9	11.8	2.1	11.8
SW	0^O	5.3	7.8	2.9	7.8
W	315^O	4.5	7.3	2.4	7.3
NW	270^O	3.2	6.3	1.7	6.2
All Wave directions		9.9	10.4	5.3	10.4
Repeated wave period 100 year					
N	225^O	7.1	8.9	3.8	8.9
NE	180^O	14.9	12.6	8.0	12.5
E	135^O	7.8	9.4	4.2	9.3
SE	90^O	6.0	13.8	3.2	13.7
S	45^O	5.8	13.6	3.1	13.6
SW	0^O	8.0	9.5	4.3	9.4
W	315^O	6.8	8.8	3.7	8.7
NW	270^O	4.9	7.5	2.6	7.5
All Wave directions		14.9	12.6	8.0	12.5

5. DYNAMIC EFFECT ASSESSMENT RESULTS

5.1 Results When Evaluating Jacket 01

Table 8 DAF_{QS} of quasi-static method - Jacket 01

Condition	Direction (degree)	T (sec)	ω (Hertz)	T_1 (sec)	ω_1 (Hertz)	DAF_{QS}
Operating	0	7.8	0.128	2.144	0.466	1.082
	45	11.8	0.085			1.034
	90	11.9	0.084			1.034
	135	7.8	0.128			1.082
	180	10.4	0.096			1.044
	225	7.4	0.135			1.092
	270	6.3	0.159			1.131
	315	7.3	0.137			1.094
Extreme storm	0	9.5	0.105	2.110	0.474	1.052
	45	13.6	0.074			1.025
	90	13.8	0.072			1.024
	135	9.4	0.106			1.053
	180	12.6	0.079			1.029
	225	8.9	0.112			1.060
	270	7.5	0.133			1.086
	315	8.8	0.114			1.061

Table 9 DAF_D of dynamic deterministic method - Jacket 01

Condition	Direction (degree)	Maximum base shear in dynamic response (kN)	Maximum base shear in static response (kN)	DAF_D
Operating	0	1502.288	1437.098	1.045
	45	890.603	880.197	1.012
	90	895.060	884.200	1.012
	135	1352.995	1307.471	1.035
	180	4122.361	3945.505	1.045
	225	1058.703	1016.381	1.042
	270	614.051	527.180	1.165
	315	1069.029	1025.461	1.042
Extreme storm	0	2910.576	2790.822	1.043
	45	1576.451	1544.959	1.020
	90	1636.661	1616.360	1.013
	135	2604.740	2501.746	1.041
	180	9859.746	9549.040	1.033
	225	2091.403	2002.906	1.044
	270	1141.690	1081.880	1.055
	315	2058.096	1949.594	1.056

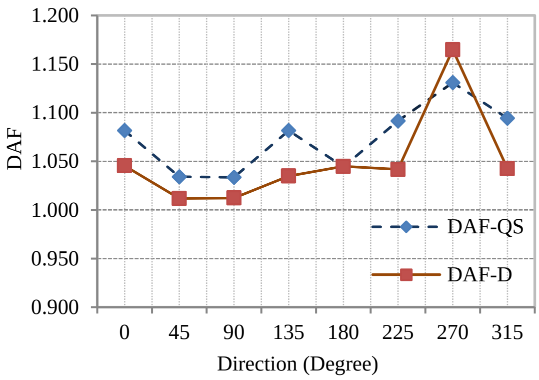

Fig. 9 Correlation between DAF_{QS} and DAF_D at operating conditions- Jacket 01

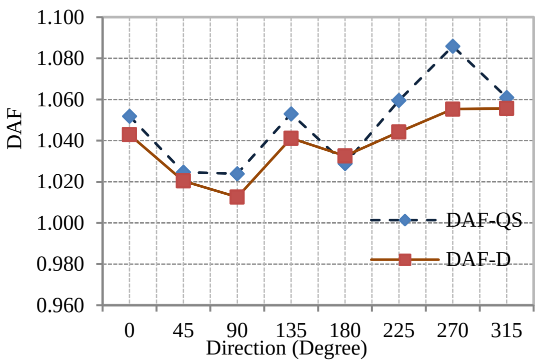

Fig. 10 Correlation between DAF_{QS} and DAF_D at Extreme storm - Jacket 01

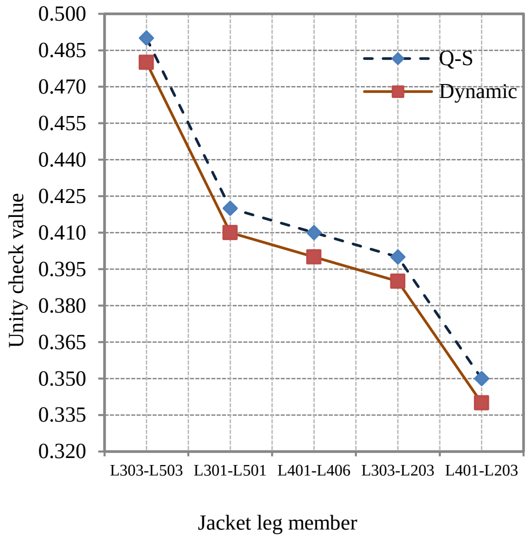

Fig. 11 Correlation representation UC of Jacket leg member, operating conditions - Jacket 01

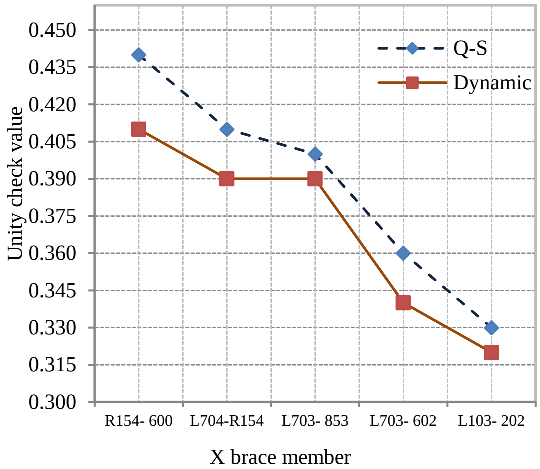

Fig. 12 Correlation representation UC of X brace member, operating conditions - Jacket 01

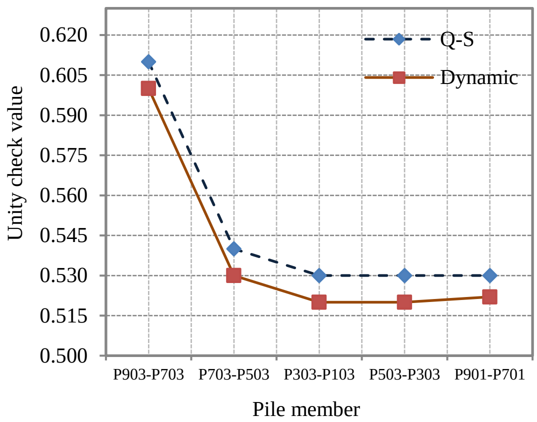

Fig. 13 Correlation representation UC of pile member, operating conditions - Jacket 01

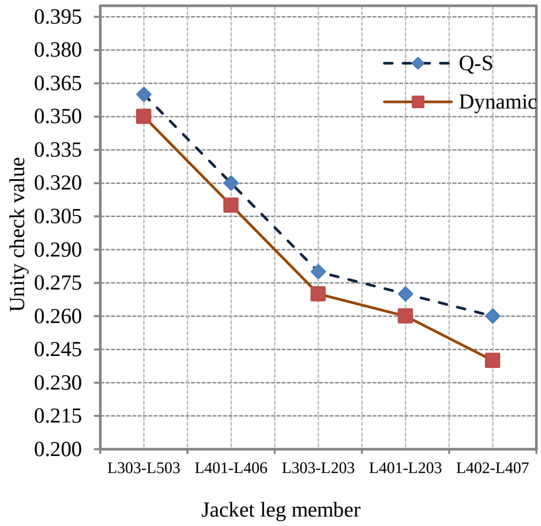

Fig. 14 Correlation representation UC of Jacket leg member, extreme storm conditions - Jacket 01

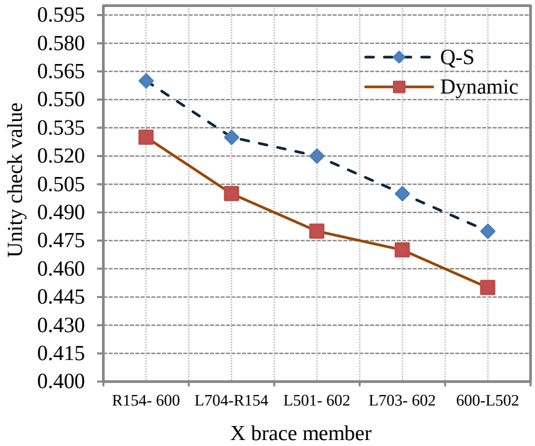

Fig. 15 Correlation representation UC of X brace member, extreme storm conditions - Jacket 01

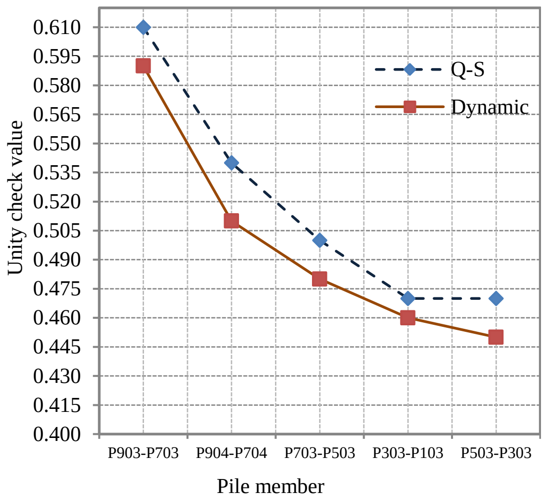

Fig. 16 Correlation representation UC of pile member, extreme storm conditions - Jacket 01

5.2 Results When Evaluating Jacket 02

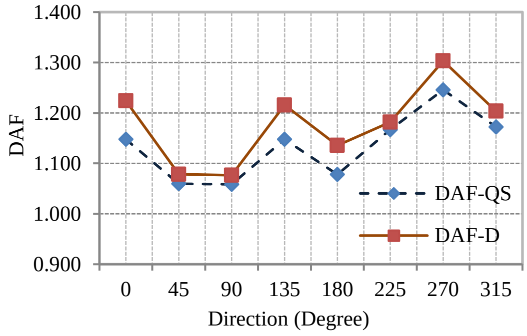

Fig. 17 Correlation between DAF_{QS} and DAF_D at operating conditions- Jacket 02

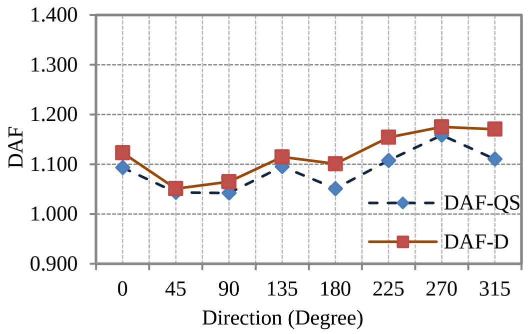

Fig. 18 Correlation between DAF_{QS} and DAF_D at Extreme storm - Jacket 02

Table 10 DAF_{QS} of quasi-static method - Jacket 02

Condition	Direction (degree)	T (sec)	ω (Hertz)	T_1 (sec)	$ω_1$ (Hertz)	DAF_{QS}
Operating	0	7.8	0.128	2.800	0.357	1.148
	45	11.8	0.085			1.060
	90	11.9	0.084			1.059
	135	7.8	0.128			1.148
	180	10.4	0.096			1.078
	225	7.4	0.135			1.167
	270	6.3	0.159			1.246
	315	7.3	0.137			1.172
Extreme storm	0	9.5	0.105	2.775	0.360	1.093
	45	13.6	0.074			1.043
	90	13.8	0.072			1.042
	135	9.4	0.106			1.095
	180	12.6	0.079			1.051
	225	8.9	0.112			1.108
	270	7.5	0.133			1.158
	315	8.8	0.114			1.110

Table 11 DAF_D of dynamic deterministic method - Jacket 02

Condition	Direction (degree)	Maximum base shear in dynamic response (kN)	Maximum base shear in static response (kN)	DAF_D
Operating	0	1790.274	1462.492	1.224
	45	1076.625	998.246	1.079
	90	1074.014	997.691	1.076
	135	1600.365	1316.458	1.216
	180	4367.083	3845.388	1.136
	225	1211.395	1025.012	1.182
	270	677.555	519.894	1.303
	315	1248.702	1037.612	1.203
Extreme storm	0	3146.470	2801.787	1.123
	45	1729.147	1645.401	1.051
	90	1787.500	1678.741	1.065
	135	2808.401	2519.405	1.115
	180	9951.420	9040.626	1.101
	225	2338.043	2026.081	1.154
	270	1280.161	1089.474	1.175
	315	2348.794	2006.716	1.170

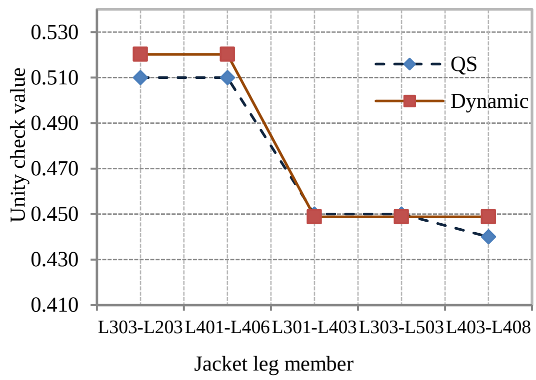

Fig. 19 Correlation representation UC of Jacket leg member, operating conditions - Jacket 02

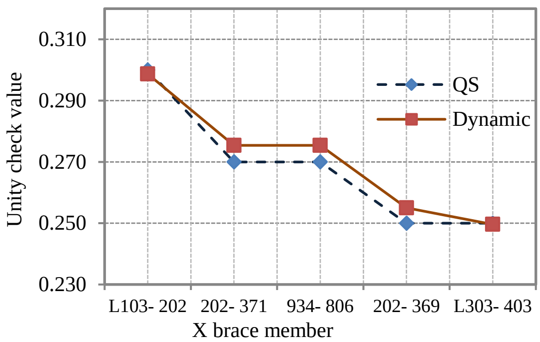

Fig. 20 Correlation representation UC of X brace member, operating conditions - Jacket 02

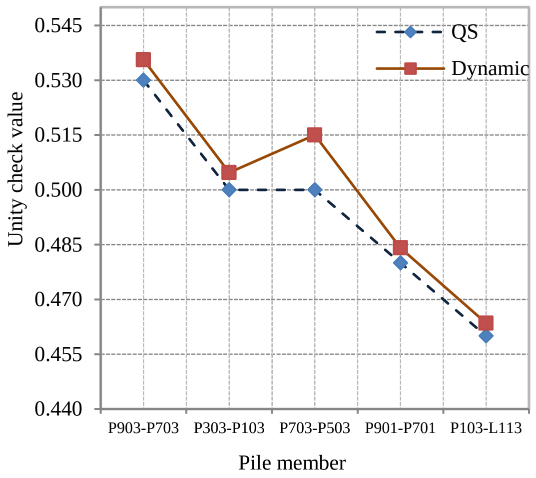

Fig. 21 Correlation representation UC of pile member operating conditions - Jacket 02

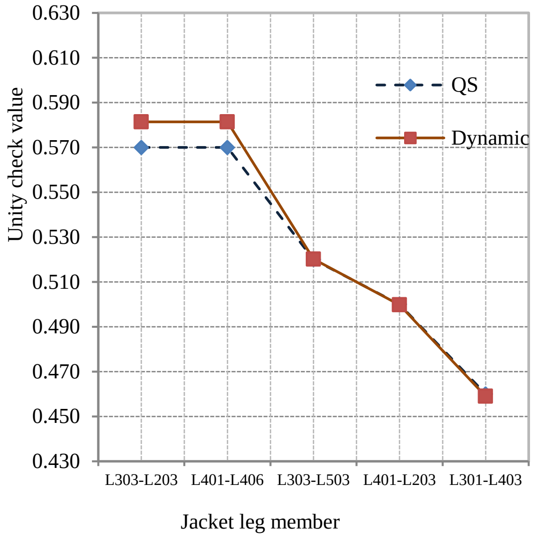

Fig. 22 Correlation representation UC of Jacket leg member, extreme storm conditions - Jacket 02

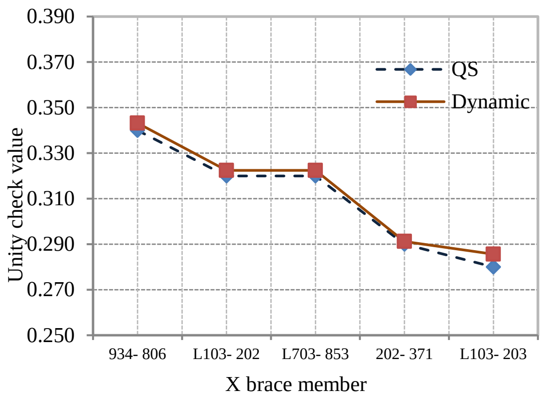

Fig. 23 Correlation representation UC of X brace member, extreme storm conditions - Jacket 02

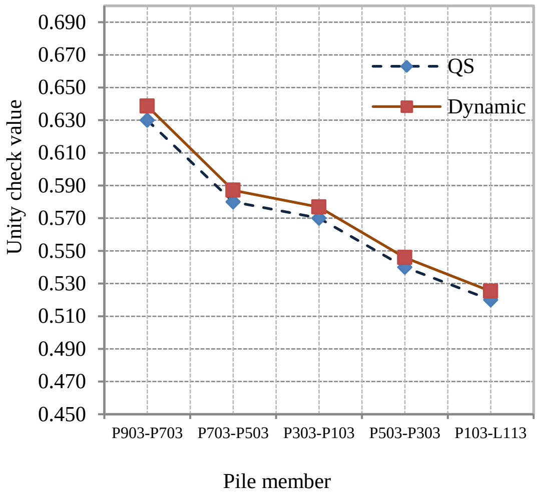

Fig. 24 Correlation representation UC of pile member, extreme storm conditions - Jacket 02

5.3 Results When Evaluating Jacket 03

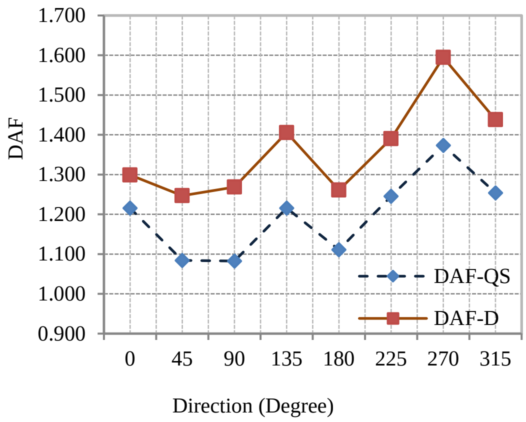

Fig. 25 Correlation between DAF_{QS} and DAF_D at operating conditions- Jacket 03

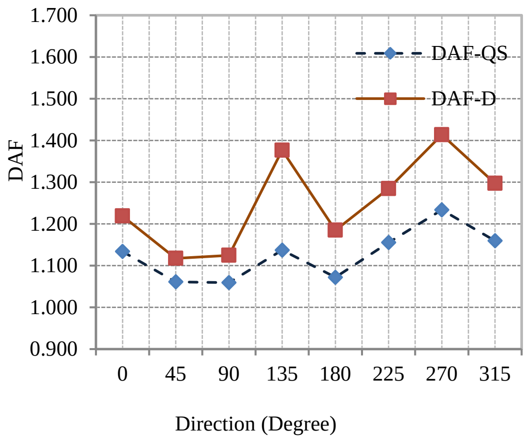

Fig. 26 Correlation between DAF_{QS} and DAF_D at Extreme storm - Jacket 03

Table 12 DAF_{QS} of quasi-static method - Jacket 03

Condition	Direction (degree)	T (sec)	ω (Hertz)	T_1 (sec)	ω_1 (Hertz)	DAF_{QS}
Operating	0	7.8	0.128	3.287	0.304	1.216
	45	11.8	0.085			1.084
	90	11.9	0.084			1.082
	135	7.8	0.128			1.216
	180	10.4	0.096			1.111
	225	7.4	0.135			1.245
	270	6.3	0.159			1.373
	315	7.3	0.137			1.254
Extreme storm	0	9.5	0.105	3.266	0.306	1.134
	45	13.6	0.074			1.061
	90	13.8	0.072			1.059
	135	9.4	0.106			1.137
	180	12.6	0.079			1.072
	225	8.9	0.112			1.155
	270	7.5	0.133			1.234
	315	8.8	0.114			1.160

Table 13 DAF_D of dynamic deterministic method - Jacket 03

Condition	Direction (degree)	Maximum base shear in dynamic response (kN)	Maximum base shear in static response (kN)	DAF_D
Operating	0	1890.456	1455.331	1.299
	45	1121.175	899.198	1.247
	90	1126.390	887.873	1.269
	135	1724.410	1226.755	1.406
	180	4676.461	3708.611	1.261
	225	1364.936	981.688	1.390
	270	751.093	471.038	1.595
	315	1406.351	977.947	1.438
Extreme storm	0	3414.651	2801.472	1.219
	45	1640.365	1468.013	1.117
	90	1658.600	1474.662	1.125
	135	3289.596	2389.939	1.376
	180	1019..235	8604.537	1.185
	225	2529.821	1969.330	1.285
	270	1411.800	998.755	1.414
	315	2473.492	1907.007	1.297

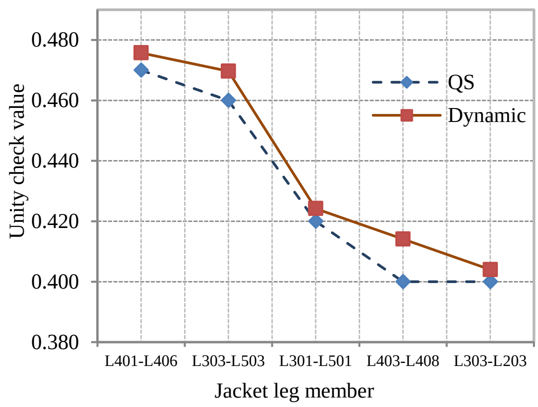

Fig. 27 Correlation representation UC of Jacket leg member, operating conditions - Jacket 03

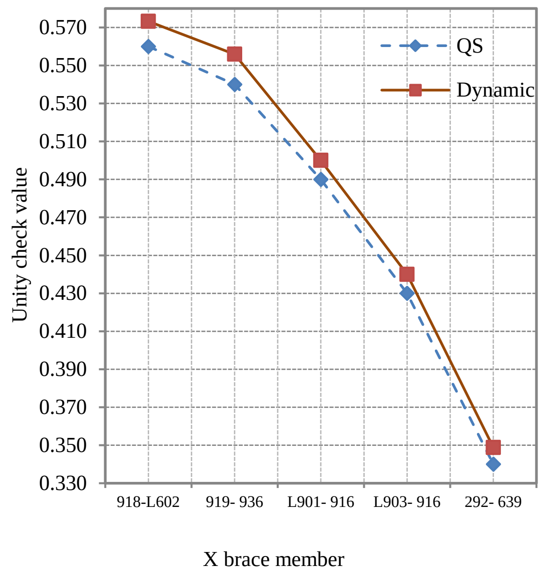

Fig. 28 Correlation representation UC of X brace member, operating conditions - Jacket 03

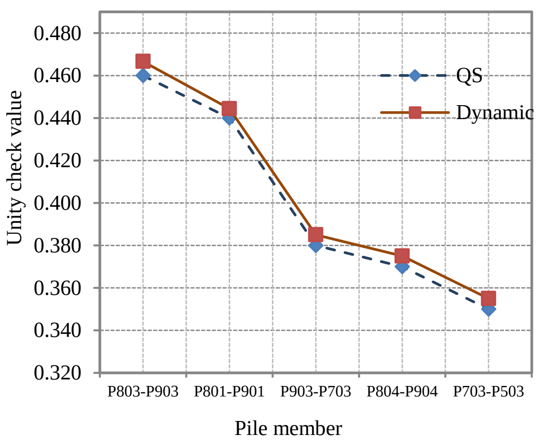

Fig. 29 Correlation representation UC of pile member, operating conditions - Jacket 03

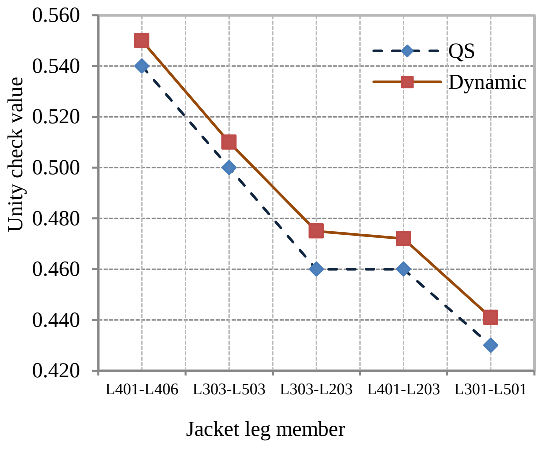

Fig. 30 Correlation representation UC of Jacket leg member, extreme storm conditions - Jacket 03

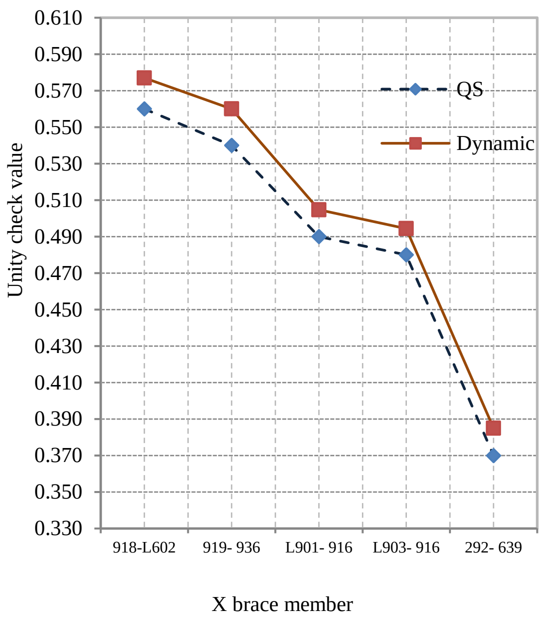

Fig. 31 Correlation representation UC of X brace member, extreme storm conditions - Jacket 03

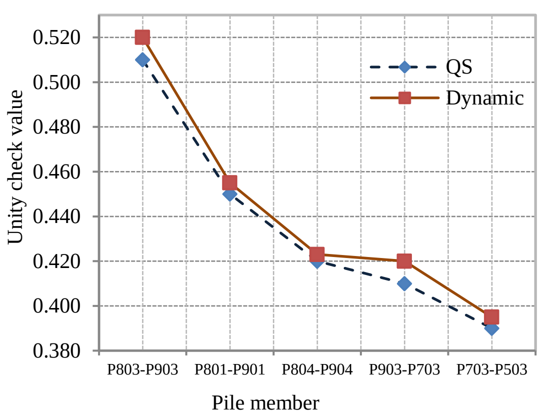

Fig. 32 Correlation representation UC of pile member, extreme storm conditions - Jacket 03

5.4 Compare the Force of Inertia

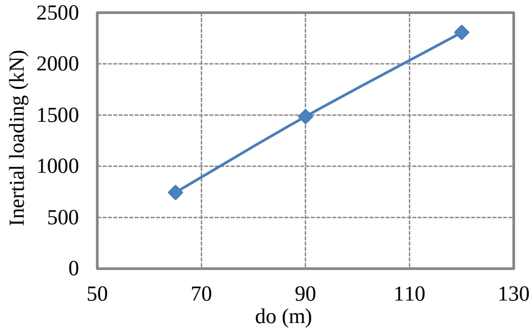

Fig. 33 Inertia force - Jacket 01, Jacket 02, and Jacket 03

Table 14 Inertia force - Jacket 01, Jacket 02, and Jacket 03

Combo	Inertia force - Jacket 01		Inertia force - Jacket 02		Inertia force - Jacket 03	
	Fx (kN)	Fy (kN)	Fx (kN)	Fy (kN)	Fx (kN)	Fy (kN)
401	-79.75	0.12	-118.22	-10.53	479.90	3.90
402	-5.89	-6.46	-10.70	-9.98	-12.70	-2.80
403	0.05	-14.02	0.29	-13.01	-0.20	-2.30
404	36.09	-26.95	29.93	-255.97	399.50	-134.60
405	183.62	20.13	306.26	4.27	391.40	37.60
406	29.84	31.88	23.76	112.72	122.20	156.90
407	-0.69	231.59	0.33	97.39	-1.40	253.90
408	-40.85	45.60	7.93	137.67	-120.10	220.40
421	-127.15	3.69	-208.72	7.61	-268.20	-41.90
422	-18.12	-31.53	-14.57	-16.12	-19.20	-20.50
423	-0.58	-31.56	-0.44	-57.05	0.20	-76.90
424	70.86	-80.06	171.08	-282.57	39.00	-583.50
425	313.23	-10.70	528.93	33.57	1283.60	-6.10
426	52.79	72.83	139.53	278.31	82.70	233.30
427	-0.15	72.56	1.22	139.44	-4.40	277.40
428	-68.90	98.66	-156.56	400.07	-22.20	308.30
Sum	743.65		1485.23		2306.41	

Table 15 The values DAF_{QS} and DAF_{D} of Jacket 01, Jacket 02, and Jacket 03

Jacket	DAF_{QS} (The average value)		DAF_{D} (The average value)		Difference between DAF_{D} and DAF_{QS} (%)	
	Operating	Extreme storm	Operating	Extreme storm	Operating	Extreme storm
Jacket 01	1.074	1.048	1.059	1.028	-1.397	-1.908
Jacket 02	1.134	1.087	1.177	1.119	3.792	2.944
Jacket 03	1.197	1.126	1.363	1.252	13.868	11.190

Table 15 and Fig. 33 show that the value of inertia force increases with water depth.

5.5 Comparison of Dynamic Effects

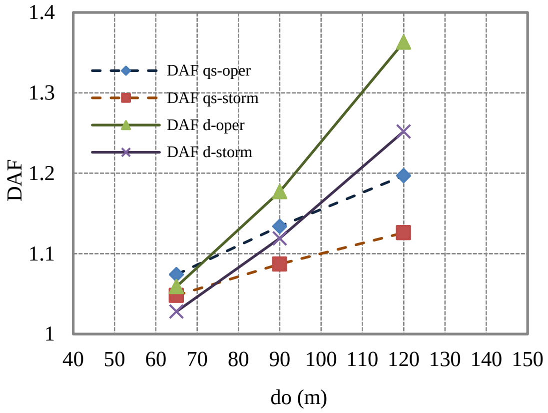

Fig. 34 The values DAF_{QS} and DAF_D of Jacket 01, Jacket 02, and Jacket 03

6. RESULTS AND DISCUSSION

The dynamic effect values of the quasi-static method (DAF_{QS}) and the dynamic method (DAF_D) are different. Different wave directions will give different dynamic effect values. Dynamic effect values corresponding to operating conditions are larger than those corresponding to extreme storm conditions. The dynamic effect values of the dynamic method (DAF_D) are larger than the dynamic effect values of the quasi-static method (DAF_{QS}) for both the analysis conditions of operating and extreme storms. However, the difference between DAF_{QS} and DAF_D dynamic effect values under extreme storm conditions is smaller than in operating conditions. Fig. 11 ÷ Fig. 16; Fig. 19 ÷ Fig. 24 and Fig. 27 ÷ Fig. 32 show that the durability test results (material utilization factor UC) also received a compatible variation with the values of DAF_{QS} and DAF_D.

The dynamic effect of dynamic analysis (DAF_D) tends to start to be greater than the dynamic effect when using the quasi-static analysis (DAF_{QS}) with a water depth of approximately greater than 70 m.

Table 15 lists and compares the results of the dynamic effects of wave loading on three Jacket structures in Vietnamese marine conditions. Figure 37 depicts the variation of the dynamic effect of wave loads on three Jacket structures with water depth. Table 15 and Fig. 34 give a visual view of the relationship between water depth and specific period of the Jacket structure with the dynamic effect of wave loading in the strength analysis of Jacket structures in Vietnam sea conditions.

The trend of the graph in Fig. 34 shows a clear change in the dynamic effect of wave loads on the Jacket structure in Vietnamese marine conditions when the water depth exceeds 70m to 75m.

7. CONCLUSION

This paper presents an algorithm to evaluate the dynamic effects of wave loads on Jacket structures through the ratio between the dynamic response and the quasi-static response of the structure under the action of sea waves. The dynamic responses of the Jacket structure were determined by the finite element method, using SACS software. The algorithm proposed in this paper has been applied to evaluate the dynamic effect of wave loads in the strength analysis for 03 Jacket structures, built at increasing water depth (from 60 m to 120 m) in Vietnam's sea conditions. Based on the research results of this paper, the authors of the paper have conclusions and recommendations on the limit to apply quasi-static method and dynamic method in strength analysis of Jacket structures at Vietnam's sea conditions as follows:

In the analysis of the durability of the Jacket structure in Vietnam sea conditions, the quasi-static method gives a larger dynamic effect than the dynamic method for the structure in the low-lying water area less than 70 m deep. In contrast, the quasi-static method results in a much smaller dynamic effect than the dynamic method for structures in water depths greater than 70 m.

The difference in dynamic effects between the dynamic method and the quasi-static method increases with water depth, specifically: With a water depth of 65 m (Jacket structure with $T_1 \approx 2.1$ s) the difference is on average - 1.39% to -1.91%; with a water depth of 90 m (Jacket structure with T1 $\approx$ 2.8 s) the average difference is 2.94% to 3.79%; with a water depth of 120 m (Jacket structure with $T_1 \approx 3.2$ s) the average difference is 11.19% to 13.87%. The dynamic effect in the strength analysis of the Jacket structure increases significantly when the water depth exceeds 70 m.

Based on the trend of the graph of Fig.34 and the results in Table 15, it shows that, with Jacket structures at water depths greater than 70 m, under Vietnamese sea conditions, the dynamic effects of dynamic stability analysis will be larger than the dynamic effect of quasi-static analysis.

The research results of this paper, combined with some practical applications in the process of designing and building Jacket structures in marine conditions in Vietnam. This paper proposes the application limits application of quasi-static and dynamic analysis methods to analyze Jacket structure in Vietnam conditions, specifically as follows:

- When the water depth is greater than 70 m, or when the natural period of the Jacket structure T_{max} > 2.5 s, in Vietnam sea conditions, it is necessary to perform dynamic analysis to ensure the safety of the structure.

- Quasi-static strength analysis should only be considered in the basic design phase.

8. REFERENCES

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