Dynamic Behaviour of a Mono-pile with Skirted Template Structure for Offshore Wind-Power System

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Abstract. The purpose of this research is to develop an offshore structural system that may sustain a stronger wave and have better stability. The object of the research is a hybrid type of offshore mono-pile-template structural system, which is more flexible and relatively easier to construct compared to the heavy mass type offshore structural system. It is expected that this hybrid type of supporting structure for an offshore wind-power generation platform will have the flexibility as presented by a typical template structural and yet, consistent properties for supporting function of the structure. Two types of structure are designed for the analytical study, namely, the mono-pile supporting structural system and the hybrid type combined with the mono-pile and the template structure as an outskirt frame system. Both annual regular waves and extreme storm waves of a 100-year return period are applied to the structural system as exerting forces.

1. Introduction
Due to the necessity for the development of offshore wind power system, it is important to find an offshore structural system that may sustain a higher wave and strong wind, and yet, have better stability during the operation of the platform. For a wind power generator installed in an offshore area, not only is the cost of installation high but the maintenance will be more complicated, especially for the safety of the structural system when it is subjected to the wave excitation, current action and mostly wind action on the generators transmitting to the supporting structure. In order to provide a safe supporting structure for an offshore wind power generator, many types of supporting system were developed, which include the gravity type, mono-pile supporting structure, multi-pile supporting structure, suction type, tri-pod supporting structure, jacket frame (template frame), floating type, and many combined types that may include two or more systems as mentioned together.
Each type of the supporting system for the offshore wind power station has its advantage and also drawback. Depending on the local environmental conditions such as seabed conditions, current and wave conditions, the applied system must be appropriately chosen to avoid the possible negative effect. The jacket frame (template frame) is a steel frame system that can be independently installed to support the offshore wind power system and it can also be combined with either a pile system or pod system. It is a flexible system in terms of its wide usage and the property of the structural system. However, according to the countable information, most construction plans proposed by the competing contractors for the possible wind-power station projects located in the late established site of wind-farm such as Taiwan Strait are mono-piles due to its economic reasons. According to the investigation that the sub-bottom sea-bed conditions for the location of most wind-power stations under plan are
mostly soft soil with thick sediments of organic material, which is weak in bearing strength and shear resistance. In order to support the wind-power generator, a mono-pile with large diameter must be applied to the foundation system, such as a size larger than five meters is usually required. For monopiles in such huge size, many difficulties under construction of infrastructure and installation for the wind-mill system will be up to another level including the mobilization, working ships like crane ship, transportation and supporting facilities around working site. Therefore, an alternative system, a combination system of mono-pile with skirted template frame is proposed and designed in this study. The jacket frame, a template system is more flexible compared to the heavy mass type offshore structural system. In the mechanical analysis, material properties must be taken into accounts for a flexible structural system and therefore, it will take more effort for the analytical works. For the flexible type template structural system, vibration mitigation could be essentially important and to overcome this problem, some innovative measures have been proposed in as early as 1990s [1,2,3,4,5]. If a combination between the mono-pile and template structural system can be applied, then the over-flexibility problem from the template structure or over-size problem from a mono-pile system can be solved through a more balanced hybrid structural system.

In this hybrid system, the vibration induced by either waves or current will be the main purpose of this study and moreover, the wind loading on the top structure that sustains the turbine system will also be considered. In the analysis, a prototype of mono-pile with skirted template structural system was established according to the power generation and environmental requirement of the typical west coastal offshore area, a presumed offshore wind farm. Along with the member size, material properties and joint types, two supporting systems are assumed, namely, the hybrid support and mono-pile support. When the turbine rotation was taken into accounts, the transmitting vibrations and forces to the supporting structure are also evaluated. From the analytical results, the comparison between an independent mono-pile system and a hybrid system combined with a mono-pile and template structural system can be made and conclusions are drawn.

2. Theorem Applied in the Study
The dynamic equation of motion for an offshore structural member with mass M, structural damping C, and stiffness K, subjected to the wave forces propagated in the normal direction of the structural member as shown in Figure 1, can be written as

\[ M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = P(t) \] (1)

where \( x(t) \) is the displacement and the one with dot and double dot is the velocity and acceleration respectively. Taking into account of the relative motion between the structures and fluids, the wave forces \( P(t) \) exerted on the structural member,[6] can be presented as follows

\[ P(t) = \rho V C_m \dot{u}(t) - \rho V C_d \ddot{\dot{X}}(t) + \frac{1}{2} \rho C_d A |u(t) - \dot{X}(t)| (u(t) - \dot{X}(t)) \] (2)

where \( C_a = C_m - 1 \), and \( u \) and the one with dot is the velocity and acceleration of the fluid normal to the structural member resulted from the horizontal and vertical motion of the fluid, respectively. \( V \) and \( A \) is the displaced volume and the projected front area of the structural member, respectively. The last term in the equation representing the drag force due to the relative velocity of fluid is nonlinear. The nonlinearity of the drag term is retained through the use of the approximate relation derived by Penzien and Tseng [7],

\[ |u(t) - \dot{X}(t)| (u(t) - \dot{X}(t)) = |u(t)|u(t) - 2 < u(t) > \dot{X}(t) \] (3)

where \( <u(t)> \) represent a time average value for the velocity of the fluid. Therefore, the wave force can further be rewritten into a form as the following

\[ P(t) = \rho V C_m \dot{u}(t) - \rho V C_d \ddot{X}(t) + \frac{1}{2} \rho C_d A (|u(t)|u(t) - 2\dot{u}(t)\ddot{X}(t)) \] (4)

After substitution of the new form of wave force into the equation of motion, it becomes a form as
By grouping the unknown terms that are to be solved on one side in the equation, the equation of motion yields into the following form as

\[ M \ddot{x} + C \dot{x} + Kx = \rho v C_m \ddot{u}(t) - \rho v C_d \dot{x}(t) + \frac{1}{2} \rho C_d A(u(t) \dot{u}(t) - 2 \ddot{u}(t) \dot{x}(t)) \]  

(5)

Now the normal motion for both structural displacements and fluids at the nodes of the structural member can be transformed into the global system for the whole structure, respectively, as

\[ (M + \rho v C_d) \ddot{x}(t) + (C + \rho C_d A \ddot{u}(t)) \dot{x}(t) + Kx(t) = \rho v C_m \ddot{u}(t) + \frac{1}{2} \rho C_d A(u(t) \dot{u}(t)) \]  

(6)

When we have the equations of motion and the forces exerted on the structural system ready, the analysis can be carried out by using the step-by-step integration schemes for the nonlinear structural system such as Newmark method \[8\], Wilson's method \[9\] etc.. In this study the Newmark method was adopted due to its stability advantage.

3. Analytical Model

An offshore template structure located in the sea can be in various forms, shapes and sizes. A typical one will be like a wedge shape or part of a pyramid of which the lower part is wider. However, a square shape like a box of template structure with vertical column-piles is also popular due to its easier to be installed. Therefore, in this study, for the purpose of enhancement of a mono-pile foundation system, a square box type of hybrid foundation of mono-pile and template infrastructural system was designed for an analytical study.

The study applied here is a case utilized by Tai-power to be applied to an offshore wind-power generator in the west coast of Taiwan, of which sizes of most members except for the vertical ones are adopted. For the purpose of this study to compare the responses of the infrastructure with or without an out-skirt frame system under various wave conditions, the thickness of the vertical members is reduced in order to have a compatible stiffness when combined with a mono-pile system.

The related dimensional data for each category of members are illustrated in Table 1. A list of geometrical data for the mono-pile is also presented in Table 2.

### Table 1 Dimensional data for the template structure

| Member | OD (mm) | ID (mm) |
|--------|---------|---------|
| vertical | 2200 | 2180 |
| horizontal | 800 | 765 |
| diagonal | 900 | 865 |

### Table 2 Geometrical data for the mono-pile

| Member | OD (mm) | ID (mm) |
|--------|---------|---------|
| Foundation | 7000 | 6940 |
| Tower/ lower | 7000 | 6940 |
| Tower/ upper | 5500 | 5440 |

During the analysis, as mentioned in the previous section, a finite element method was applied. In addition, a lumped mass method was also adapted for the dynamic analysis. Shown in Figure 1 is the analytical model for the numerical analysis of mono-pile system, where as illustrated in the figure, a mono-pile type of supporting structural system with wedge-shape in the upper part is presented. There are two sections in the pile, namely, the upper section with a wedge shape and the lower section with an uniform area. The cross section of the upper part with the wedge shape begins with a diameter of 5.5 m up to 7.0 m in a length of 30 meters, while the cross section of the lower part of the pile is uniform with diameter of 7.0 m all the way to the seabed. The analytical model was further simplified into a lumped model of three degree of freedom system for dynamic analysis as shown in the left hand side of Figure 1. Numbers in the circle represent a node along with lumped mass accumulated in the related section (as indicated in a square box) for the dynamic analysis.

For the comparison, a second infrastructure of hybrid type combined with a mono-pile and out-skirt template (frame) structural system is presented in the right hand side of Figure 1. The out-skirt template structure is proposed according to an equivalent manners for a compatible mono-pile system. The span of the template structure is 16 m and the height is 21 m while a two-layer of cross bracing...
were installed to reinforce the lateral resistant capability. The whole structure is made of steel and therefore, the property for a typical steel material was applied to the study. In order to simulate an on-situ environment, a typical environment of offshore water was applied, where the water depth is around 32 m and wave conditions: H=6.6 m, L=168 m are obtained from a 100 years return period data base. For the annual average waves, the wave height H=1.5 m, the wave length L=75.75 m.

![2-D model for the analytical study for the two types of structure](image)

**Figure 1** 2-D model for the analytical study for the two types of structure

### 4. Analytical Results

The major responses to be observed from the dynamic analysis will include mainly the displacement, velocity and acceleration of the structure while the exerting forces will include both the wave of annual average and the maximum wave of 100 years return period.

Since the structure is symmetric at each direction, a three dimensional analysis can be simplified into a two dimensional one. The wave force calculated through the Airy theorem for small amplitude linear wave is applied. The maximum wave force can reach as high as 1500 kN on the top level of the template supporting structure near the water surface level while the other level submerged under the water may reach 500 kN.

![Displacement response for the mono-pile](image)

**Figure 2** Displacement response for the mono-pile structure

![Displacement response for the hybrid mono-pile-template structure](image)

**Figure 3** Displacement response for the hybrid mono-pile-template structure

Figure 2 shows the displacement response for the upper three levels (as node 7, 6, node 5) of the mono-pile structure. The movement of the structure seems to be minor when subjected to the wave force as presumed and calculated through Airy theorem. The maximum displacement occurs at the top level, where the value is about 1.23 cm that is not significant, probably due to the large rigidity of the vertical piles. The displacement for the lower second level of the platform is about 0.96 cm.

Figure 3 also shows the displacement response for the upper three levels of the hybrid mono-pile-template structural system. The displacement of the hybrid structure subjected to the waves seems to be very similar to the mono-pile system except for a smaller value at each corresponding levels was
found. The maximum displacement occurs at the top level, where the value is about 1.1 cm that is not significant either. The displacement for the lower second level of the platform is about 0.88 cm.

Similarly, the time history of velocity for the upper part of various levels of both structures, namely, 4 mono-pile and the hybrid type with mono-pile and template structure, is also presented in Figure 4 and Figure 5. Again the maximum response occurs at the top level of both supporting structures, which is about 2.284 m/s and 1.985 m/s corresponding to the mono-pile type and the hybrid type supporting structures, while the velocity response at the second level of the platform is not significantly reduced for the mono-pile system compared to the hybrid type of supporting system.

A design wave of 100 years return period is applied in the second analysis. The displacement responses corresponding to the lower level (close to the wave motions) of structures for both structures are presented in Figure 6 and Figure 7 respectively. For the levels under analysis most close to the wave motions, namely node 4 for the mono-pile and node 9 for hybrid type of mono-pile-template structure respectively, we found that the displacement is 1.184 cm and 1.064 cm correspondingly.
A phenomenon of significant directional motion for the displacement is observed in this analysis. The motion of the supporting structure near the water surface moves along with the wave and tends to have larger amplitude in one direction than the other.

In the velocity response, a comparison between two types of structural system is also presented in Figure 8 and Figure 9. The velocity response of positions at the structure is same as the displacement responses. For the mono-pile structure the velocity at the near water level is 4.22 m/s and 3.338 m/s for the hybrid mono-pile-template structure. It is also found that the fluctuations of the velocity in hybrid system is much smaller and better mitigated, especially for the large frequency motions, compared to the mono-pile system.

5. Conclusions
During the comparison for two systems subjected to two storm conditions, namely, annual regular storm and a storm of 100-year return period, some phenomena were found as follows:
1. Both systems subjected to regular annual waves have very small responses in both displacement and velocity. However, out-skirted template structure of the hybrid system may reduce the responses by 10%.
2. For the designed waves of 100-year return period, the displacement response may reach as large as five times. The reduction for the displacement response from the outskirt frames is more or less than 10%, similar to the case subjected to an annual regular wave condition.
3. For the velocity response, the amplitude can be reduced by 21% for the hybrid system, which is larger than the reduction in displacement response. Nevertheless, a subtler vibration mode in velocity was also found in the hybrid system such that the fluctuations are mitigated and high frequency motion is reduced.

Therefore, it is concluded from the results of this study that the installation of an outskirt template structure can enhance the stability of a mono-pile supporting structural system. The enhancement will be benefit in the high frequency motion and the motion close to resonant frequency of supporting structure.

6. References
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