However, the dynamic seismic analysis will take lots of time requiring repetitive structural analysis on the estimation of the response surface and the reliability analysis. By using the peak response factor which is defined as a ratio of dynamic response to static response, the time issue can be solved with dynamic effects(Lee and Kim, 2014).

In this study, the reliability analysis with peak response factor for the dynamic effects was conducted. The seismic load, soil property, and peak response factor were considered as probability variables, and a limit state function was defined by the response surface method. Through the defined limit state function, the reliability analysis with First-Order Reliability Method (FORM) was conducted (Hasofer et al., 1974). The probability variables other than the normal distribution was defined by Rackwitz-Fiessler method for mean and standard deviation (Rackwitz and Fiessler, 1978). A jacket structure used for oil drilling for a long time was used for an example. The reliability analysis results from Level III with peak response factor was assumed true and applied. In this study, the real structure with multi Degree Of Freedom (DOF) was used to verify the peak response factor, while a single degree of freedom model was used in Lee and Kim's study (2014). The conventional Monte Carlo Simulation(MCS) requires lots of trials and many application difficulties are expected. The MCS based Latin Hypercube Sampling(LHS) was used in this study, which requires relatively less trials to produce satisfying results. The FORM was also conducted considering the peak response factor with dynamic properties as a constant to review the effect on the results.

2. Theory

2.1 Reliability analysis

The reliability analysis can be sorted as three levels according to designer's requirements: Sampling method (Level III) that produces lots of random sampling numbers to get the probability of failure in a direct way; Approximate solution (Level II) around the failure point using the defined limit state function; Safety evaluatioin (Level I) in a simple way by applying the factors to the load function and the resistance function. The Level III method can produce a relatively accurate probability of failure but it requires many samples because the probability of failure used to be very low from the engineering point of view.

2.2 Response surface method

To perform the reliability analysis, a limit state function should be defined by the probability variables and the structural response such as deflection and rotation are considered as dependent variables. The limit state function defined by the variables are expressed in the form of implicit function and it makes the analysis difficult. The Response Surface Method (RSM) can approximate the limit state function into the explicit function to make analysis easier (Scheuller et al., 1987). The response surface can be obtained by selecting the sample points in a constant interval from the center, and performing structural analysis from those points. (Khuri and Cornell, 1987). Each sample point can be expressed by Eq. (1).

$$\mathrm{X_i} = \mathrm{X_i^{\mathit{C}}} \pm \mathrm{h_i}\sigma_{X_i} I_i \tag{1}$$

Where, X_i^C and σ_{X_i} are the mean and standard deviation of variable X_i, respectively, and h_i is the expansion width, I_i is the scattering index.

2.3 Peak response factor

The dynamic peak response and the joint probability density function $f_{R_p,X}$ are expressed by Eq. (2). The damage probability P_f is a volume of the probability density function where the limit state function belongs to negative numbers, and expressed by Eq. (3).

$$f_{R_p,X} = f_{R_p|X}(r_p|x)\, f_X(x) \tag{2}$$

$$P_f = \int_{g<0} f_{R_p,X}(r_p, x) dr_p dx = \int_{-\infty}^{\infty} f_{R_p|X}(r_p|x) f_X(x) dr_p dx \tag{3}$$

In Eq. (2), $f_X$is a probability density function of each variable, $f_{R_p|X}$ is a probability density function of dynamic peak response to corresponding variables. x and r_p are one variable and a dynamic peak response corresponding to the variable. g in Eq. (3) is a limit state function.

The reliability analysis requires repetitive structural analysis until getting convergent reliability index. In general, a static response is used because getting dynamic peak response every time is not easy. In this study, to apply the existing method considering the dynamic effects, a ratio of dynamic peak response (R_p) to static response (R_{st}) was used as shown in Equation 4. The ratio (R_n) is called a Peak Response Factor (PRF).

$$R_n = R_p / R_{st} \tag{4}$$

From the Eq. (4), under the assumption that the dynamic peak response is proportional to the static response when the dynamic features does not change according to the stochastic variables, the limit state function can be defined by Eq. (5).

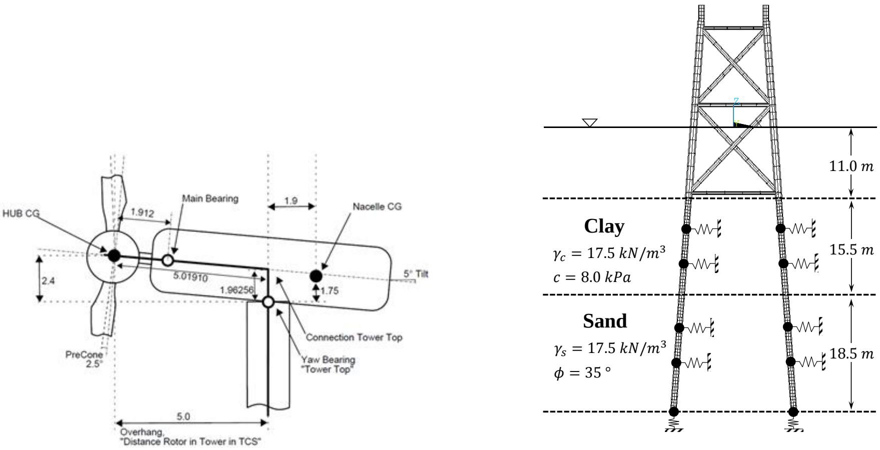
$$g(X) = R_{all} - R_n R_{st} \tag{5}$$

Expressing the peak response factor and the joint probability density function of variables, and the limit state function on the normal distribution space, the reliability index (β) which is the shortest distance between the origin and the failure surface can be obtained.

3. Numerical analysis

3.1 Model and environmental condition

A commercial program ANSYS Ver. 12.0 (Ansys Inc, 2009) was used for modeling and numerical analysis. A 5MW offshore wind turbine of NREL(National Renewable Energy Laboratory) reference model(Jonkman et al., 2009) was used. A jacket structure was used to accord with the environmental condition in South west coast in Korea. A beam element was used for tower and jacket, and the Rotor and Nacelle (RNA) was converted into a concentrated mass on each center of gravity by mass element as shown in Figure. 1(a).



(a) Center of gravity for RNA (b) Finite element model and soil profile

Fig. 1 Offshore Wind Turbine and Soil Profile

3.1.1 Foundation model

As shown in Figure. 1(b), the supports are connected with the foundation composed of cohesive soil and sandy soil, which have a depth of 15.5 m and 18.5 m, respectively. In general, when a load is applied to a structure, a displacement happens along the load direction and also foundation reaction happens to resist the displacement. The relationship between the load and displacement increases non-linearly. To express the nonlinear effect of the foundation, the API RP 2A(American Petroleum Institute, 2007) recommends the *p-y* curve considering the pile diameter and the effective specific weight.

A *p-y* curve for cohesive soil is listed in Table 1, and the ultimate bearing force (p_u) by Eq. (6) is used for *p-y* curve. Where, X, c, D, γ and J are the depth from the surface, undrained shear strength, pile diameter, effective specific weight and experience constant, respectively. X_R is a critical depth calculated by Eq. (7). y_c is a parameter of the critical displacement calculated by Eq. (8). ε_c is a constant strain corresponding to a half of the maximum stress from the undrained compressive test.

Table 1 p-y curves under cyclic loading

$X > X_R$		$X < X_R$	
p/p_u	y/y_u	p/p_u	y/y_u
0.00	0.0	0.00	0.0
0.23	0.1	0.23	0.1
0.33	0.3	0.33	0.3
0.50	1.0	0.50	1.0
0.72	3.0	0.72	3.0
0.72	∞	0.72 X/X_R	15.0
-	-	0.72 X/X_R	∞