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Equivalent static transformation of wave inertia force for FE analysis of SFT

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ABSTRACT

In this study, wave inertia force from Morison's equation is transformed into an equivalent static pressure distribution, for more efficient section design of SFT. Considering the ratio of dimension to wavelength smaller than 0.2, Morison's equation can be adopted to express the wave load. Values of response amplitude operators (RAO) and phases at each circumferential node in a circular SFT section are provided by solving wave diffraction theory. Validation of the transformed wave inertia force is performed by comparing the resultant force of the transformed load with the maximum dynamic force calculated by the maximum acceleration of fluid at the same submergence depth. In this process, regular waves ranged from 6 s to 15 s of frequencies are used. Consequently, the potential of equivalent static load for FE analysis of SFT and reliability of the suggested approach is investigated.

1. INTRODUCTION

An SFT is located in water, and therefore it is structurally safer than sea bridges and has the advantage of low construction cost compared to immersed tunnels. The SFT located in the deep submergence is subjected to high water pressure, and in order to evaluate the behavior of the SFT, it is necessary to accurately define the complex interaction between the surround fluid and the structure. (Dean 1948; Brancaleoni 1989) For example, Svein *et al.* analyzed the behavior of structures by considering diffraction and radiation terms of wave loads. (Svein 1999). However, in the case of performing dynamic analysis to investigate the specific response caused by the elastic behavior of a structure, in detail, sectional stress or internal energy, huge computational resources are required, and thus, it is very inefficient and takes a long time.

In order to solve these limitations, various studies have been conducted such as improvement of the finite element method, and numerical analysis of the SFT based on lumped-mass and spring elements (Jin 2020). In particular, when the ratio of the diameter

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of the structure to the wavelength of the wave load is less than 0.2, Morison's equation can be introduced because the structure has little effect on the wave propagation (Sarpkaya 1986). This Morison's equation divides the wave load into three terms: inertia force, added mass force, and drag force (Fartinsen 1993). Among these, the term of drag force is greatly affected by the structure shape and surrounding environment, but in the case of inertia force, there is little difference according to Morison's equation and diffraction problem solving, therefore it can be converted into static form through linear wave theory (Subrata 2007; Marit 2012).

In this study, to reduce the computational resources required for the dynamic analysis of SFT and to evaluate the detail response, the inertia force term among the components of the wave load was converted into an equivalent static component. The RAO and phase values were checked for each node along the circumferential direction, and these values were obtained by solving the wave diffraction theory. The verification of the transformation result was conducted by comparing the maximum value of the resultant force that appears when solving the dynamic analysis. For the whole process, regular waves with a period of 6 to 15 seconds were used, and OrcaFlex, a commercial analysis program, was used (Orcina, 2018). Consequently, the potential of equivalent static load for FE analysis of SFT and reliability of the suggested approach is investigated.

2. REGULAR WAVES

A regular wave can be defined as the function of harmonic oscillation, therefore, transformation of dynamic waves into the equivalent static loads can be easily validated compared to the that of irregular wave. The velocity potential of the fluid Φ can be expressed as:

$$\nabla^2 \Phi = 0 \tag{1}$$

four boundary conditions to solve the equation (1) can be easily found in wave diffraction theories (Fartinsen 1993). The wave force can be calculated by integrating the dynamic pressure through the circumference of the SFT as follows:

$$p = Re[i\omega\rho\Phi^{i\omega t}] \tag{2}$$

where ρ is density of the fluid, *Re* means the real part in the bracket. On the other hand, validation of wave inertia force is conducted by comparison of the values from solving boundary value problem and the same component obtained from OrcaFlex (Orcina, 2018). For comparing the wave inertia force at each frequency, regular waves with period from 6 s to 15 s are chosen. By solving the boundary value problem, the wave inertia force can be calculated as:

$$F_{inertia} = \frac{H}{2}\, Mag\, A_{circ} \,/\, L_{total} \tag{3}$$

where *H* is wave height, *Mag* is magnitude of wave inertia force, A_{circ} is circumferential area of unit length and L_{total} is total length of the SFT in longitudinal direction. Besides, OrcaFlex evaluate the wave inertia based on the Morison's equation:

$$F_{inertia} = \rho c_m V \ddot{\eta} \tag{4}$$

where c_m is coefficient of the wave inertia force (= 2.0), *V* is unit volume of the SFT and $\ddot{\eta}$ is acceleration of fluid. The program directly evaluates the $\ddot{\eta}$ when the input parameters for regular waves (wave height, period, etc.) are determined. Consequently, by comparing two terms of the wave inertia forces, the transformed equivalent wave loads can be validated.

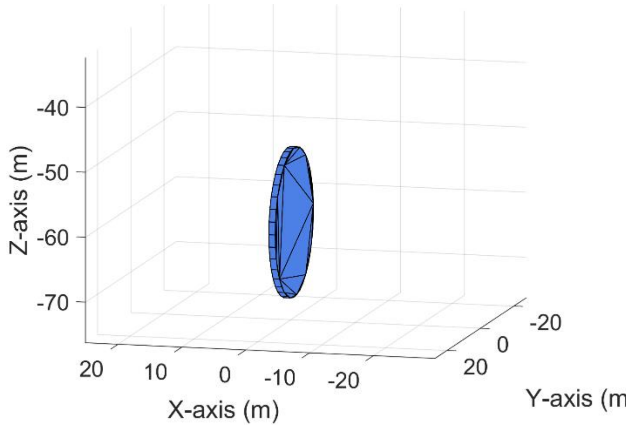

Fig. 1 Example of 3-D panel for solving wave diffraction problem

3. ANALYTICAL RESULT

Table 1. Theoretical comparison of results from wave diffraction problem and OrcaFlex

Period (s)	Max Acc. (m/s^2)	$F_{inertia}$ (kN)	Magnitude (kN/m)	$F_{inertia}$ (kN)	Error (%)
6	0.00283	2.41	18	2.6	7.92
7	0.0129	10.99	82	11.94	8.64
8	0.03247	27.66	204	29.48	6.6
9	0.05856	49.88	372	53.76	7.78
10	0.08662	73.78	539	77.89	5.58
11	0.11304	96.28	694	100.29	4.17
12	0.13567	115.55	900	130.06	12.55
13	0.15349	130.73	1,010	145.96	11.65
14	0.16651	141.82	1,090	157.52	11.07
15	0.17519	149.22	1,150	166.19	11.38

Table 1 shows the comparison result of wave inertia force based on regular waves in submergence depth of 61.5 m. As mentioned above, the period of regular wave is distributed from 6 s to 15 s. The second and third columns mean the maximum acceleration of the fluid and the wave inertia force calculated by OrcaFlex. Next, the fourth and fifth columns are the magnitude value and wave inertia force calculated by solving the wave diffraction problem. The last column indicates the error rate between the two results. The overall error is around 10% and in case of short periods such as 6s or 7s, and up to 11s, error rate is lower than 5%. However, long period waves are seemed to govern the structural behavior of the SFT, which is a gigantic structure in dimension, therefore, giving more weighting factor in long period waves is reasonable. However, 10% rate is still lower than the expected value for the first trial, and the result means the generated equivalent static load is little bit bigger and conservative design of the structure can be performed.

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