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Equivalent static transformation of dynamic wave load for FE analysis of SFT

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ABSTRACT

When a structure is submerged in a certain depth of water, the structure suffers high level of hydrostatic pressure and additional dynamic load induced from surface wave. Description of wave load can be categorized into the two types, such as regular and irregular waves, and magnitude and phase of the wave is determined by two characteristic parameters, significant wave height and period. For FE analysis of the submerged floating tunnel (SFT), which is aimed to the easier parametric approach of design of SFT section in longitudinal and circumferential direction, transformation of dynamic wave load into the equivalent static form is needed for preventing the time-consuming analytical process of dynamic FE analysis. In this study, with solution of boundary value problem and additional inhouse code based post-process, equivalent static wave load is generated and validated by comparison of the summation of pressure.

1. INTRODUCTION

An SFT is defined as a tunnel which floats in water by the equilibrium between its weight and buoyancy force. When the SFT is located in deep submergence, it will be subjected to a high level of hydrostatic pressure (Dean 1948) and additional dynamic loads induced from wave, which oscillate as functions of various frequencies and interact with the submerged structure in terms of radiation and diffraction (Svein 1999). Especially, complex characteristics of wave loads interacting with the elastic deformation of the submerged tunnel, which can be represented by wave inertia, added mass and damping loads, make it almost infeasible to assess the load and resistance factor for a section design.

According to the previous studies, the structural analyses of SFT have been performed on the basis of the dynamic equilibrium equation in which the dynamic loads are described by the Morison's equation (Sarpkaya 1986; Jin 2020). However, since the entire structure is based on the use of linear beam elements for the main tunnel structure

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and linear beam or truss elements for the mooring lines, respectively, the obtained analytical results of the given SFT structure will be limited to the longitudinal direction only and cannot cover the entire member forces required for the design of SFT. Since design of a typical section in the transverse direction must be based on the member forces in the circumferential direction which cannot be obtained from the longitudinal global analysis, another analytical approach to evaluate the member forces in the transverse direction must be supplemented in addition to the longitudinal analysis.

In this study, transformation of dynamic wave loads into the equivalent static form is suggested for the FE analysis of the SFT. With solution of boundary value problem and additional inhouse code based post-process, equivalent static wave load is generated, and each load is validated by comparison of the summation of adopted force. Through the development and validation of the equivalent analytical approach, section design of SFT will be efficient and cost-effective.

2. REGULAR AND IRREGULAR WAVES

Transformation of dynamic waves into the equivalent static loads can be separated as two parts: a) validation of inertia term and b) generation of equivalent static irregular wave.

Validation of inertia term means that generated equivalent wave from solving boundary value problem is compared with the same component obtained from the commercial program, OrcaFlex (Orcina, 2018). To compare the wave inertia force at each frequency, regular waves are selected with its period from 6 s (1.047 rad/s) to 15 s (0.419 rad/s). Wave inertia force from the boundary value problem can be calculated as:

$$F_{inertia} = \frac{H_s}{2}\, Mag\; A_{circ} \,/\, L_{total} \qquad (1)$$

where H_s is significant height of wave, Mag is calculated magnitude of wave inertia through the boundary value problem, A_{circ} is circumferential area of unit span length, and L_{total} is total length of the SFT in longitudinal direction. On the other hand, commercial program OrcaFlex calculates the wave inertia based on the Morison's equation:

$$F_{inertia} = \rho c_m V \ddot{\eta} \qquad (2)$$

where ρ is density of fluid, c_m is inertia coefficient (2.0), V is unit volume of the structure and $\ddot{\eta}$ is acceleration of fluid. OrcaFlex directly calculates the acceleration of fluid when the input parameters for regular waves (wave height, period, etc.) are determined. Therefore, through the comparison of two $F_{inertia}$ terms, the equivalent wave loads from solving the boundary value problem can be validated.

After that, for considering the randomized wave phases and wave frequency spectrum, JONSWAP spectrum, which is one of the irregular waves, is generated. Differently from the regular wave cases, theoretical comparison was not conducted, but validation of each wave case is carried out through the summation of reaction forces on analytical results. Fig. 1 shows one of the equivalent static irregular wave pressure distribution, affecting on the unit section of SFT by using commercial analytical program, ABAQUS (Dassault, 2007).

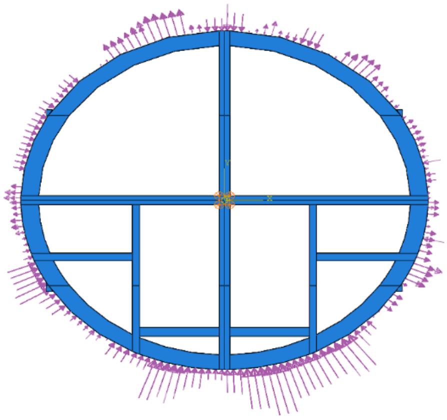

Fig. 1 Equivalent static irregular wave pressure distribution

3. CONCLUSIONS

Table 1 shows the theoretical comparison of wave inertia force from regular waves. The first column describes each period, and the second and the third columns describe results obtained from OrcaFlex. Also, the fourth and the fifth columns show results from the boundary value calculation. As the last column shows, error rate is around 10%. In case of short period such as 6s or 7s, and up to 11s, error rate is relatively low, but for SFT, which is quite gigantic structure in dimension, long period waves are seemed to govern the structural behavior of the SFT. Therefore, it is quite reasonable to give more weighting factor in long period waves. However, around 10% error rate is lower than the expected value as the first trial, and this means that the generated equivalent static load is slightly bigger so that conservative design of the structure can be achieved.

Table 1. Theoretical comparison of results from boundary value problem and OrcaFlex

Period (s)	Max Acc. (m/s^2)	$F_{inertia}$ (kN)	Magnitude (kN/m)	$F_{inertia}$ (kN)	Error (%)
15	0.17519	149.22	1,150	166.19	11.38
14	0.16651	141.82	1,090	157.52	11.07
13	0.15349	130.73	1,010	145.96	11.65
12	0.13567	115.55	900	130.06	12.55
11	0.11304	96.28	694	100.29	4.17
10	0.08662	73.78	539	77.89	5.58
09	0.05856	49.88	372	53.76	7.78
08	0.03247	27.66	204	29.48	6.60
07	0.01290	10.99	82	11.94	8.64
06	0.00283	2.41	18	2.60	7.92

Table 2 shows the irregular wave validation results. The validation was performed through the comparison between two commercial programs, OrcaFlex and ABAQUS. As the regular wave cases, OrcaFlex analyzes the structure adopting the Morison's equation, and generated equivalent static wave pressure, as described in the Fig. 1, was adopted by using ABAQUS. Using exactly same model of SFT, which has 200m total length, tensile forces on four mooring lines at mid-span are summated and compared.

As the table shows, difference between two analyses is extremely small, much more than expected at first, and seemed to be induced by two reasons. The first important point is the hydrostatic load, which is calculated by summation of buoyancy force and weight of the SFT. Due to the gigantic scale of the structure (in this example, 23m in diameter), hydrostatic force term is around 66,299 kN, which occupies from 81% to 99% of the total forces. Therefore, error rate will be much higher than the current results. Secondly, the motion effect should be considered. With the acceleration of SFT (not fluid acc.), tunnel inertia force will be calculated and the magnitude and its direction will differ the results.

Table 2. Analytical results of tensile forces between OrcaFlex and ABAQUS

Irregular wave condition (H_s, T_p)	**OrcaFlex (kN)**	**ABAQUS (kN)**	**Error (%)**
11.7m, 13.0s	81,649.8	81,364.3	-0.35
10.0m, 11.5s	79,445.6	79,623.2	0.22
8.0m, 10.0s	75,628.1	75,596.0	-0.04
6.0m, 8.0s	69,803.5	69,782.1	-0.03
3.5m, 5.0s	66,460.0	66,299.7	-0.24

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