

Article

Experimental Study on Enhanced Serviceability for Human Activities of Floating Structures with Wave-Dissipating Modules

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Abstract: This study evaluates the serviceability of floating structures designed for marine cities by incorporating wave-dissipating modules. Small-scale model tests in a 2D wave flume were conducted to compare the serviceability of structures with and without these modules under different wave conditions (1-year and 100-year return period waves). The results showed that wave-dissipating modules significantly reduced vertical acceleration, with reductions of approximately 44~45% levels for 1-year return period waves and 54~57% levels for 100-year return period waves. When a topside building was included, the reductions were similarly pronounced, reaching 64% and 63~64% levels for 1-year and 100-year return period waves, respectively. The modules also mitigated inclination (angle), with reduction rates ranging from 55~77% levels, depending on wave conditions and the presence of a topside building. These findings suggest that incorporating wave-dissipating modules around the periphery of floating structures can enhance their serviceability by creating more comfortable and stable environments for human activities, while also improving the stability of the structures themselves. Future research should focus on scaling up the model tests and conducting field experiments to validate these findings under real conditions, as well as optimizing module designs for different wave conditions and structural configurations.

Keywords: floating structure; wave-dissipating module; serviceability; human comfort; vertical acceleration; inclination (angle)



Academic Editor: Joshua Omer

Received: 8 January 2025

Revised: 17 February 2025

Accepted: 17 February 2025

Published: 19 February 2025

Citation: Jeong, Y.-J.; Park, M.-S.; Kim, Y.-T.; Kim, J. Experimental Study on Enhanced Serviceability for Human Activities of Floating Structures with Wave-Dissipating Modules. *J. Mar. Sci. Eng.* **2025**, *13*, 385. <https://doi.org/10.3390/jmse13020385>

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1. Introduction

Recently, there has been an increasing trend of interest and demand for floating offshore infrastructure in terms of environmentally friendly utilization of maritime space. Floating offshore infrastructure can be largely classified into industrial facilities such as industrial plants and ports, as well as those intended for human activities such as floating cities. Up until now, floating structures have been widely used for industrial facilities, such as ports for container loading and energy storage platforms for oil and LNG. Additionally, there is a growing trend to apply floating renewable energy hubs to renewable energy complexes, such as offshore wind farms, as part of projects like Denmark's Net-zero race project, in order to compensate for the intermittency issues of renewable energy. The serviceability guidelines for floating infrastructure intended for industrial facilities primarily focus on inclination (angle), aiming to ensure the stable operation of topside by preventing equipment failures and malfunctions [1].

In addition to industrial facility uses, there has been a recent movement to construct floating marine cities, such as the Saudi Arabian NEOM city project. In floating marine cities, unlike industrial facility uses, continuous human activity and habitation take place, making the impact of floating structure motion on human comfort (such as seasickness and other discomforts) a major issue. Therefore, in floating structures focused on human activity, controlling the motion of the floating structure to a level that ensures human comfort is referred to as serviceability. To prevent physical discomfort experienced by humans, serviceability guidelines based on vertical acceleration due to the floating structure's motion are provided [1,2]. These serviceability guidelines for human activity-focused floating structures are not only applied to floating marine cities but are also expanding into areas such as floating offshore wind farm and other maritime industrial facilities to ensure the health and safety of maintenance personnel [3,4].

To improve the serviceability of floating infrastructure, it is necessary to reduce the wave motion of the floating structures, and various studies have been conducted in this regard. Xiao et al. [5] reported that perforated walls have a significant impact on reducing the pitch behavior and wave run-up of floating structures through experimental studies on floating structures with perforated walls. Yao [6] reported that the hydro damping effect of perforations formed on the bottom surface of the floating body can reduce wave motion. Han and Wang [7] studied the reduction of wave energy by floating breakwaters with slitted openings, while Chen et al. [8] conducted a study on reducing the motion of pontoon type floating bodies by applying damping plates to reduce the size and weight of the floating bodies. In addition, many studies have been conducted on reducing the motion of floating offshore wind platforms (semi-submersibles) using damping plates [9–12].

Bi et al. [13] conducted an analytical study by installing a vertical tensioned sheet barrier at the front of the floating body to stabilize its motion. Gayathri et al. [14] researched the reduction of wave forces acting on a floating bridge by installing a vertical partial flexible barrier at the front of the floating bridge. Liu and Li [15] studied the hydrodynamic behavior characteristics of a double curtain-wall breakwater system composed of a seaward perforated wall and a shoreward impermeable wall.

In addition to mechanical methods based on the shape of the floating body (or secondary modules), there has been a growing interest and research in nature-based methods for wave dissipation [16–18]. Nature-based wave-dissipation methods using seaweed, shellfish farming, etc., around the floating body can be environmentally friendly and cost-effective. However, they may have limitations in terms of accessibility of ships and sustainability depending on the season (typhoon, seawater temperature changes). Therefore, nature-based damping methods are still being attempted for coastal protection and marine aquaculture farms in response to climate change, rather than for large floating infrastructures such as industrial facilities, floating cities, and ports.

This paper proposes a method to reduce wave motion by placing wave-dissipating modules on the outer edges of a floating structure designed for marine cities. The serviceability indexes with and without the wave-dissipating modules were evaluated and analyzed through a 2D wave flume test. The serviceability indexes focused on the vertical acceleration related to the discomfort of residents and the inclination for the stable operation of topside (buildings).

2. Serviceability of Floating Structures

2.1. Serviceability Guideline and Evaluation

Germany's Aachen University and the UK's Cranfield University have analyzed various serviceability guidelines for the motion of marine structures (including ships) through the EU Horizon 2020 project, to establish guidelines for the impact of floating structures

motion on human activities during maintenance of floating offshore wind platforms [3,4]. According to their research results, the requirements for serviceability guidelines applicable to human activities on floating offshore wind platforms are the following: first, they must include the frequency range of 0.1~0.5 Hz, which is the floating structure's motion period; second, they must provide reference values for vertical motion (acceleration), which is a major component of human discomfort. It is also stated that the serviceability guidelines for the motion of ships [19] and fixed offshore structures are difficult to apply directly to floating structures.

Therefore, the guidelines applicable to the serviceability assessment related to floating structure motion with a focus on human activities during the maintenance of floating offshore wind platforms are approximately at the level of ISO 2631-1:1997 [20]. Although the Nordforsk [21] are aimed at ships, they are often referenced in various fields of research related to human operability on actual floating offshore platforms and are worth considering [3,22]. In addition, NR 636 [23] provides guidelines on habitability and comfort for humans on floating structures, but it reports limitations in that no reference values for vertical motion are provided and the frequency range is applicable only within 1 to 80 Hz.

(1) RMS acceleration in vertical direction

ISO 2631-1:1997 [20] provides guidelines on the impact of all forms of vibration (motion) on the human body in the form of frequency-weighted RMS (Root Mean Square) acceleration. The frequency range for human health or comfort is specified as 0.5 to 80 Hz, and the frequency range for seasickness is specified as 0.1 to 0.5 Hz [20,24]. In general, vibrations (motions) that begin to make humans feel uncomfortable have an acceleration of approximately 0.315 to 0.63 m/s² (see Table 1). The impact of vibrations on human health and comfort, depending on exposure time, is depicted and presented as the “health guidance caution zone” in Figure 1. According to this, at a vibration exposure time of 24 h, caution is required at an acceleration of 0.25 m/s², and at an exposure time of 4 to 8 h, caution is required at an acceleration of approximately 0.5 m/s² [25].

Table 1. Reactions to vibration magnitudes.

Acceleration	Human Comfort Level
<0.315 m/s ²	not uncomfortable
0.315~0.63 m/s ²	a little uncomfortable
0.50~1.0 m/s ²	fairly uncomfortable
0.8~1.6 m/s ²	uncomfortable
1.25~2.5 m/s ²	very uncomfortable
>2 m/s ²	extremely uncomfortable

The frequency-weighted RMS acceleration reflects the frequency-dependent nature of the impact of vibrations (motions) on human comfort, and it is presented as an evaluation indicator in major guidelines such as ISO, ABS, and NR [3,4,24]. The frequency-weighted RMS acceleration is calculated using the frequency-weighting function [3,4,26] as shown in Equation (1), and the overall process for calculating the frequency-weighted RMS acceleration is shown in Figure 2 [3,4,27–29].

$$a_w = \left\{ \frac{1}{T} \int_0^T [a_w(t)]^2 dt \right\}^{1/2} \quad (1)$$

where, α_w represents the frequency-weighted RMS acceleration, $\alpha_w(t)$ represents the time-domain signal of frequency-weighted acceleration, which is the measured acceleration signal multiplied by the frequency-weighting function as presented in Figure 3 [20,26], and T represents the acceleration measurement time. Additionally, some guidelines, such as Nordfors [21], use un-weighted RMS acceleration as an evaluation indicator.

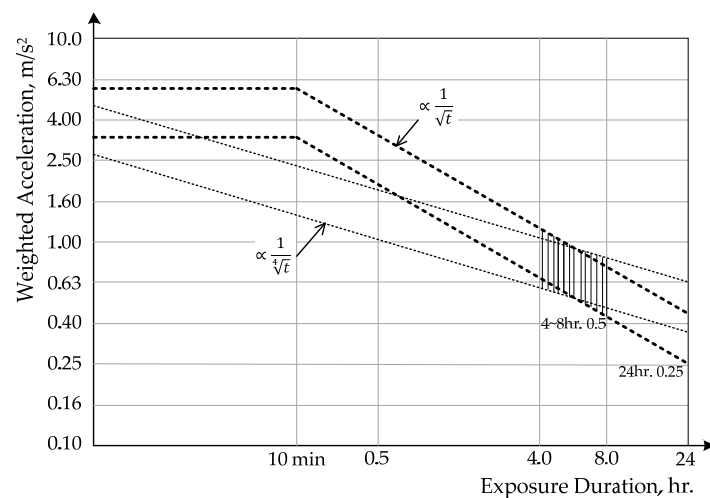


Figure 1. Health guidance caution zone.

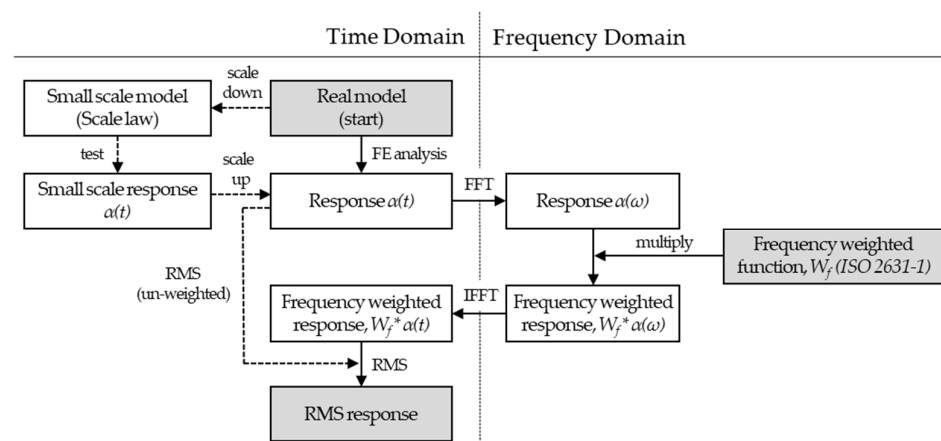


Figure 2. Evaluation process of frequency-weighted RMS acceleration [3,4,27–29].

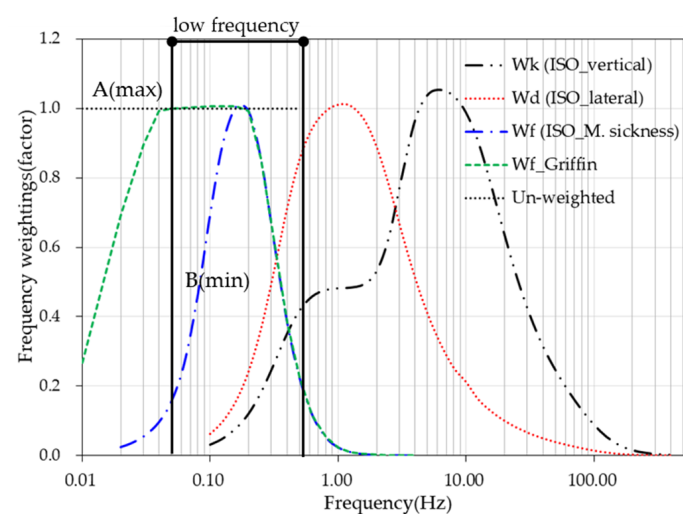


Figure 3. Frequency-weighted functions.

(2) Inclination (angle)

The serviceability criteria for the inclination of floating structures are partially presented. The Japanese Mega-Float project provides inclination criteria of 1.0° for offshore runways and 1.5° for offshore roads [30]. The Nordforsk project [21] presents RMS inclination criteria of $2.0\sim 2.5^\circ$ for human activities on the floating structure, such as cruise liners and transit passengers, and $3.0\sim 6.0^\circ$ for intellectual and manual work. Additionally, DNV [31] specifies an inclination criterion of 5° for floating offshore wind turbine. Considering these inclination criteria comprehensively, an inclination criterion of 1.5° is suitable for areas requiring the same level of flatness as land, 2.0° for human activities, and $3.0\sim 6.0^\circ$ for workability and the stable operation of topsides.

2.2. Enhanced Serviceability Using Wave-Dissipating Module

This paper proposes a method to improve serviceability by reducing the wave motion of the main floating structure by placing wave-dissipating modules on the outer edges of the main floating structure, as presented in Figure 4. The wave-dissipating module consists of external slits and internal buoyancy cells in Figure 4b; the slits are designed to dissipate wave energy, and the buoyancy cells are intended to ensure their self-buoyancy.

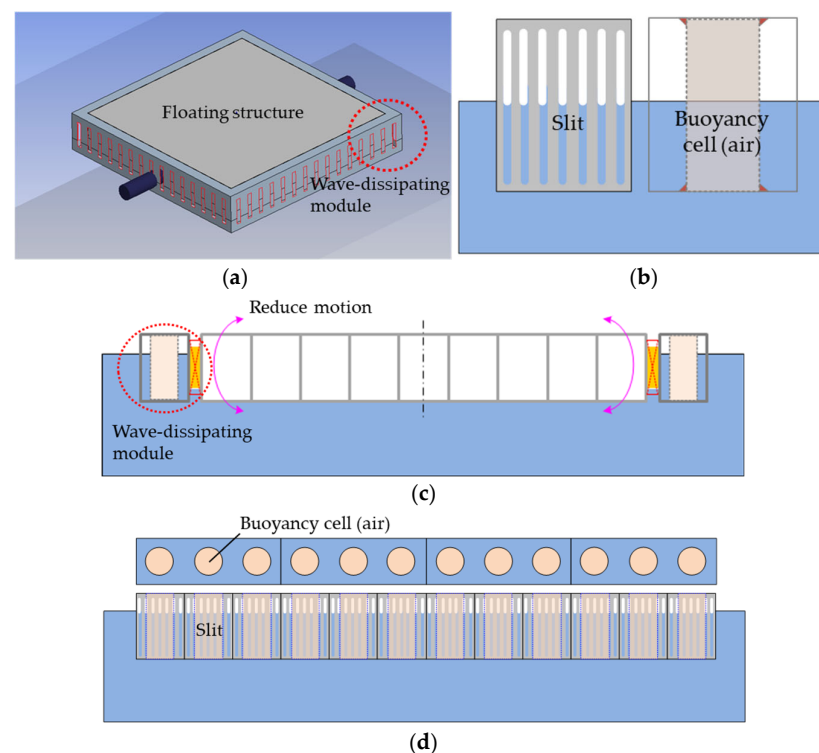


Figure 4. Floating structure with wave-dissipating module: (a) Concept model; (b) Wave-dissipating module detail; (c) Side view; (d) Front and plan view.

To increase wave energy dissipation efficiency, the slits apply 30% porosity, and the buoyancy cells have a cylindrical shape. Regarding the decision of porosity on the wall of wave-dissipating model, Korea applies a perforated wall with an approximate porosity of 30%, considering ease of construction and hydraulic characteristics [32]. KICT [32] presents the hydraulic characteristics of perforated walls based on various porosity combinations.

Previous studies aimed at reducing the wave-induced motion of floating bodies can be broadly classified into three groups: vertical barriers [13–15], heave plates [8–12], and perforated (porous) members [5–7]. The vertical barrier method has the disadvantage of the vertical barrier being difficult to secure, which is separate from the floating body, and

is unfavorable in deep water. The heave plate method is an efficient method for reducing vertical motion (heave) in vertically-oriented floating bodies, such as spar and columns in semi-submersible types, but it is less effective for horizontally-oriented pontoon-type floating bodies, as in this study. The perforated (porous) member method is suitable for pontoon type floating bodies, but the perforated members do not have their self-buoyancy, affecting the freeboard and draft of the main floating body, necessitating a greater height for the main floating body. The wave-dissipating module in this study is an appropriate method for reducing motion in pontoon type floating bodies, as it possesses its self-buoyancy, which does not affect the freeboard and draft of the main floating body, allowing for optimal design of the main floating body.

3. Small-Scale Tests

3.1. Test Models and Set-Up

To evaluate the wave motion of the floating structure and its serviceability, 2D wave flume test was conducted. The model tests were performed at Korea Institute of Civil Engineering and Building Technology (KICT) in Korea. The length, width, and height of the wave flume is 50 m, 0.8 m, and 1.5 m, respectively, and the active absorption type wave generator is installed in the wave flume. Figure 5 shows the schematic sketch of wave flume.

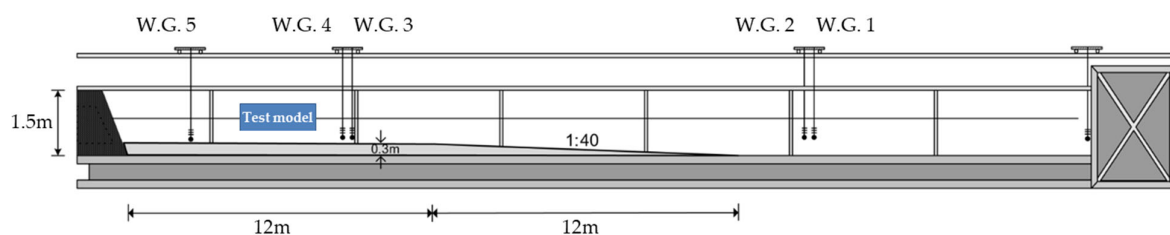


Figure 5. Wave flume schematic sketch.

The test model was designed based on the floating marine city design shown in Figure 6, applying a Froude similarity ratio of 1/50. To investigate only the unidirectional motions of heave and pitch in the 2D wave flume test, only half the width of 1 unit was manufactured. The detailed specifications of the test model are shown in Table 2. The test model was categorized into four cases according to the combination of floating structure, topside, and wave-dissipating module, as shown in Table 3. The floating structure and wave-dissipating module were connected by steel rods.

Table 2. Dimension of test models.

Items	Dimension (m) (L × W × H)	Weight (kg)	Etc.
1. Floating structure	1.20 × 0.60 × 0.22	64.80	-
2. Topside	0.96 × 0.60 × 0.40	50.46	-
3. Wave-dissipating modules	0.60 × 0.10 × 0.22	1.88	1EA/end side
4. Buoyancy cell	D0.05		

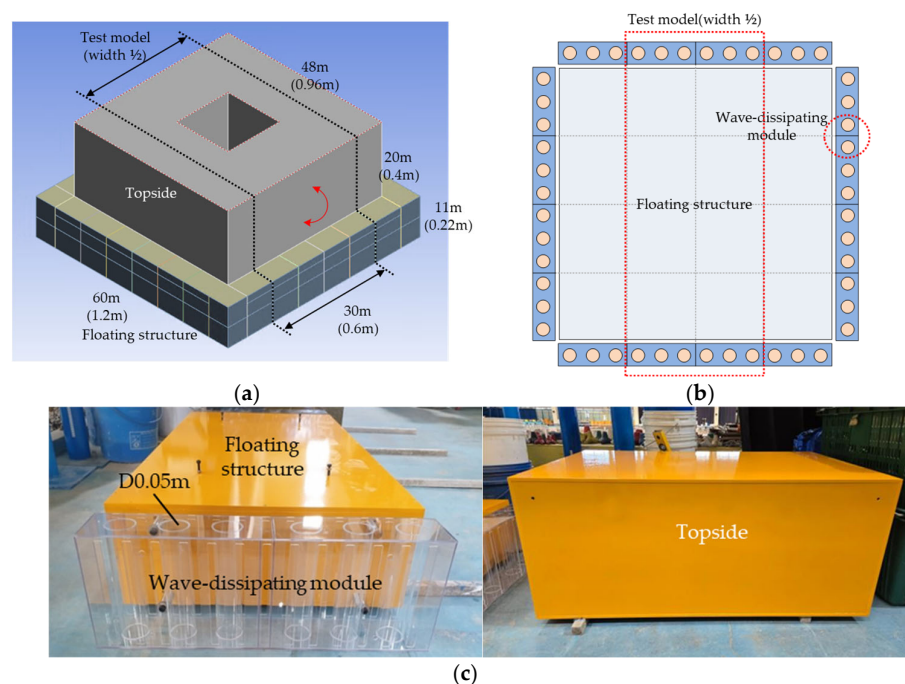


Figure 6. Test model: (a) Bird view; (b) Plan view; (c) Test model fabrication.

Table 3. Test model cases.

Cases	Test Models		
	Floating Structure	Topside Building	Wave-Dissipating Module
CASE 1-1	○	-	-
CASE 1-2	○	-	○
CASE 2-1	○	○	-
CASE 2-2	○	○	○

The installation of the test model in the 2D wave flume is shown in Figures 5 and 7. The main objective of this experiment is to measure the free-body motion of the floating structure. However, to minimize the surge motion of the floating structure due to wave loads, a mooring system using a wire rope connected to a weak spring was applied to allow semi-free body motion. The weak spring-wire mooring was connected to the four corners of the floating body, as shown in Figure 8. Consequently, the surge motion of the floating body was minimally restricted, while the heave and pitch motions, which are the main measurement items of this study, were allowed. This represents semi-free body motion. The influence of the weak spring-wire mooring used in this study on the heave and pitch motions of the floating body is considered to be minimal, and it is deemed an appropriate method to identify the influence of the wave-dissipation modules on the free body motion of the floating body. The floating structure's motion was measured accurately using a motion capture system with ultraviolet cameras. Additionally, inclinometers were installed at the center and four accelerometers at the corners of the floating structure for further measurements.

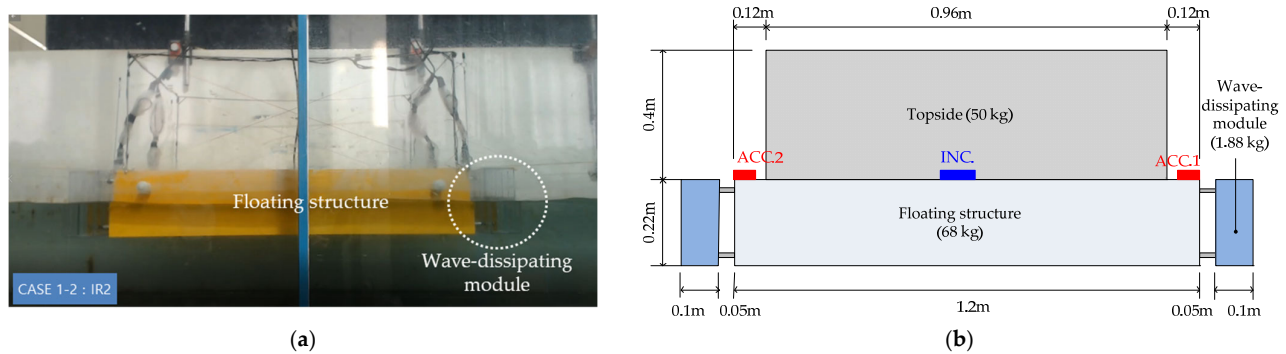


Figure 7. Test model set-up: (a) Test model set-up; (b) Sensors installation.

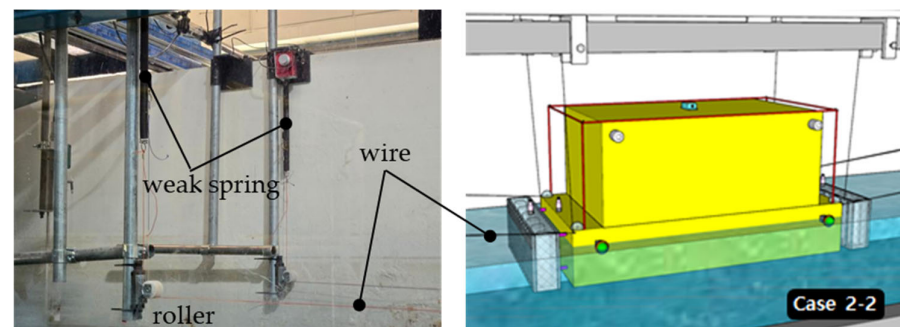


Figure 8. Weak spring-wire mooring system.

3.2. Wave Conditions

Wave loads were based on the design conditions of 1-year return period wave loads and 100-year return period wave loads, as shown in Table 4. The serviceability criteria for floating structures are based on the recommendations of project authorities, and many projects or guidelines apply the assessment for a 1-year return period wave. Therefore, this paper reflects these guidelines and conducts a serviceability evaluation for a 1-year return period wave. Additionally, to identify the effectiveness of the wave-dissipation modules, a serviceability evaluation was also conducted for the extreme condition of a 100-year return period wave. Although various periods were tested based on the wave conditions in Table 4, this paper analyzes only the two design wave conditions. The floating structure's response in regular waves was used only for analyzing floating structure fundamental motions, while the serviceability assessment analyzed irregular waves, representing actual sea conditions. The water depth used was 20 m, and it was scaled down to 0.4 m. In still water conditions, the freeboard and draft of the CASE 1 series are 0.126 m and 0.094 m, respectively, while the freeboard and draft of the CASE 2 series are 0.057 m and 0.163 m, respectively.

Table 4. Wave condition (Irregular wave: JONSWAP $\gamma = 3.3$).

No.	T_p (s.) Small (Real)	H_s (cm) Small (Real)	L (cm) Small (Real)	H/L	Return Period
R1	0.85 (6.0)	2.6 (130)	110 (5500)	0.0236	Regular
R2	1.13 (8.0)	4.2 (210)	177 (8850)	0.0237	Regular
IR1	0.85 (6.0)	2.6 (130)	110 (5500)	0.0236	Irregular (1 yr.)
IR2	1.13 (8.0)	4.2 (210)	177 (8850)	0.0237	Irregular (100 yr.)

The free water surface was measured with the capacity type wave gauges. The separation of incident and reflected waves were performed at two locations (W.G. 1 and 2 and W.G. 3 and 4 in Figure 5) by Goda and Suzuki [33]. The transmitted wave was

measured with the wave gauge 5 (W.G. 5). The irregular waves were generated with JONSWAP wave function.

3.3. Maximum Acceleration Position

To assess the serviceability regarding human comfort, it is recommended to use the acceleration values measured at the corners of the floating structure, where the most unfavorable acceleration values are typically observed, with a measurement duration of at least 2 min for low-frequency areas below 2 Hz [34]. Consequently, the maximum acceleration location was determined to evaluate the serviceability of the floating structure using the experimental results. The acceleration time history data for the bow and stern are shown in Figure 9.

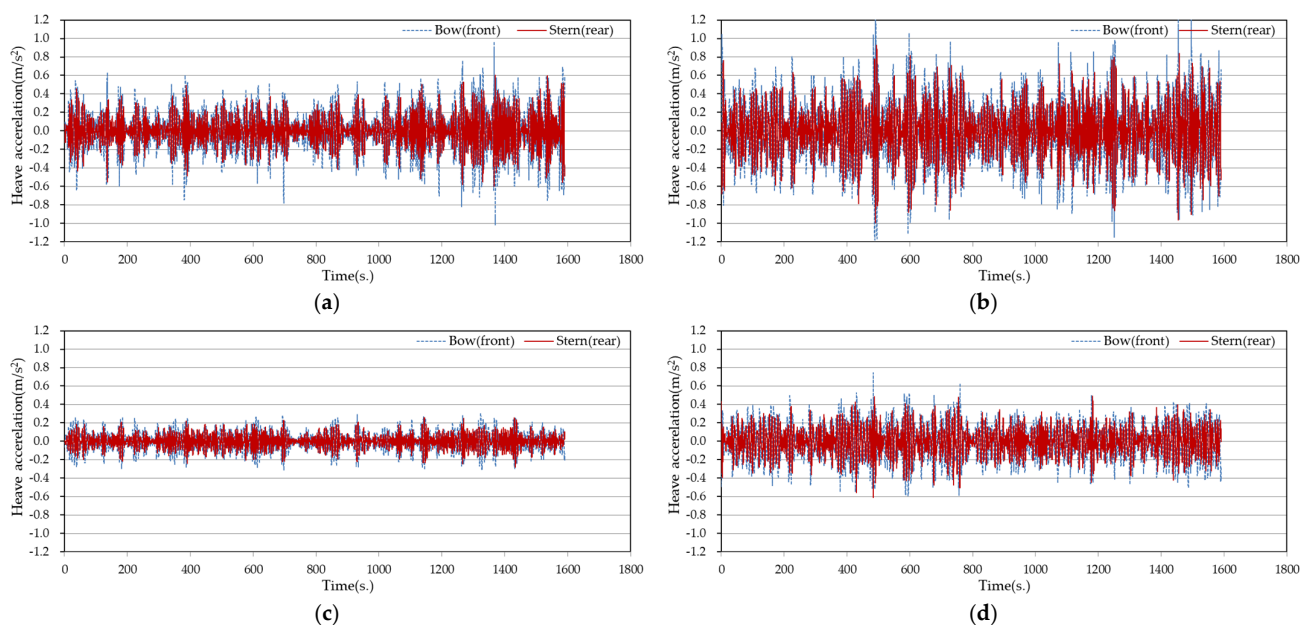


Figure 9. Measured accelerations: (a) CASE 1-1 (1 yr.); (b) CASE 1-1 (100 yr.); (c) CASE 1-2 (1 yr.); (d) CASE 1-2 (100 yr.).

Upon analysis, it was found that the bow exhibited slightly higher acceleration values overall; therefore, the bow was selected as the representative location for serviceability evaluation related to vertical acceleration. The absolute maximum acceleration for CASE 1-1 (floating structure) was 1.018 m/s^2 for the 1-year return period wave load and 1.615 m/s^2 for the 100-year return period wave load, respectively. For CASE 1-2 (floating structure combining with wave-dissipating module), the absolute maximum acceleration was 0.317 m/s^2 for the 1-year return period wave load and 0.746 m/s^2 for the 100-year return period wave load, respectively.

4. Evaluation of Serviceability

4.1. Evaluation of Serviceability for Prototype Without Wave-Dissipating Module

(1) RMS accelerations

For the CASE 1-1 test model (only the floating structure), the vertical acceleration time history and the corresponding RMS acceleration analysis for a wave load with a 1-year return period are shown in Figure 10 and Table 5. The serviceability evaluation for vertical acceleration indicated that RMS acceleration A (which means frequency un-weighted) was approximately 0.224 m/s^2 , and RMS acceleration B (which means frequency-weighted by ISO2631-1: 1997) was approximately 0.212 m/s^2 . The ratio of the RMS value to the

mean value was approximately 1.29~1.30, and RMS acceleration B was about 95% of RMS acceleration A. The vertical acceleration time history and the serviceability evaluation results for a wave load with a 100-year return period are shown in Figure 11 and Table 5. The serviceability evaluation results for vertical acceleration indicated that RMS acceleration A was approximately 0.352 m/s^2 , and RMS acceleration B was approximately 0.315 m/s^2 . The ratio of the RMS value to the mean value was about 1.24~1.25, and RMS acceleration B was about 90% of RMS acceleration A.

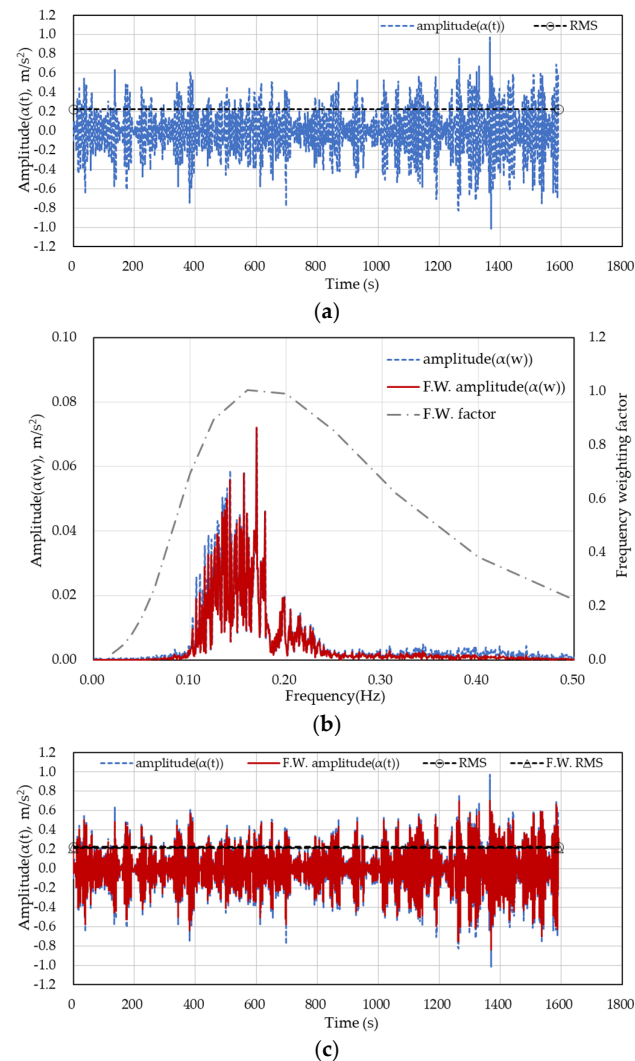


Figure 10. RMS acceleration of CASE 1-1 (1 yr.: $H_s = 1.3 \text{ m}$, $T_p = 6.0 \text{ s}$): (a) Measured acceleration (blue line); (b) Response spectrum; (c) Frequency-weighted acceleration (red line).

For the CASE 2-1 test model (floating structure combining with topside (building)), the vertical acceleration time history and RMS acceleration analysis results for a wave load with a 1-year return period are shown in Figure 12 and Table 5. The serviceability evaluation results for vertical acceleration indicated that RMS acceleration A was approximately 0.119 m/s^2 , and RMS acceleration B was approximately 0.107 m/s^2 . The ratio of the RMS value to the mean value was about 1.27, and RMS acceleration B was about 90% of RMS acceleration A. The vertical acceleration time history and the serviceability evaluation results for a wave load with a 100-year return period are shown in Figure 13 and Table 5. The serviceability evaluation results for vertical acceleration indicated that RMS acceleration A was approximately 0.271 m/s^2 , and RMS acceleration B was approximately 0.217 m/s^2 .

The ratio of the RMS value to the mean value was about 1.24, and RMS acceleration B was about 80% of RMS acceleration A.

Table 5. Summary of RMS accelerations for prototype.

Items	1 yr. ($H_s = 1.3$ m, $T_p = 6.0$ s.)				100 yr. ($H_s = 2.1$ m, $T_p = 8.0$ s.)			
	RMS acc. A		RMS acc. B		RMS acc. A		RMS acc. B	
	CASE 1-1	CASE 2-1	CASE 1-1	CASE 2-1	CASE 1-1	CASE 2-1	CASE 1-1	CASE 2-1
MAX	1.018	0.428	0.835	0.361	1.615	1.491	1.086	0.729
RMS	0.224	0.119	0.212 (0.95)	0.107 (0.90)	0.352	0.271	0.315 (0.90)	0.217 (0.80)
AVG	0.172	0.094	0.164	0.084	0.282	0.219	0.253	0.175
RMS/AVG	1.30	1.27	1.29	1.27	1.25	1.24	1.24	1.24

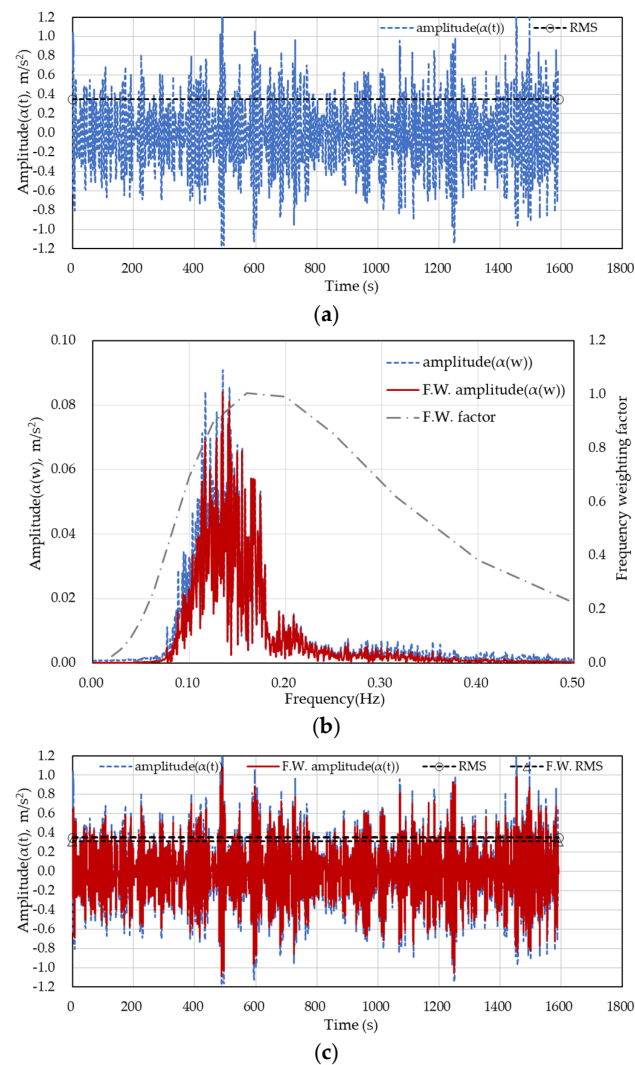


Figure 11. RMS acceleration of CASE 1-1 (100 yr.: $H_s = 2.1$ m, $T_p = 8.0$ s.): (a) Measured acceleration (blue line); (b) Response spectrum; (c) Frequency-weighted acceleration (red line).

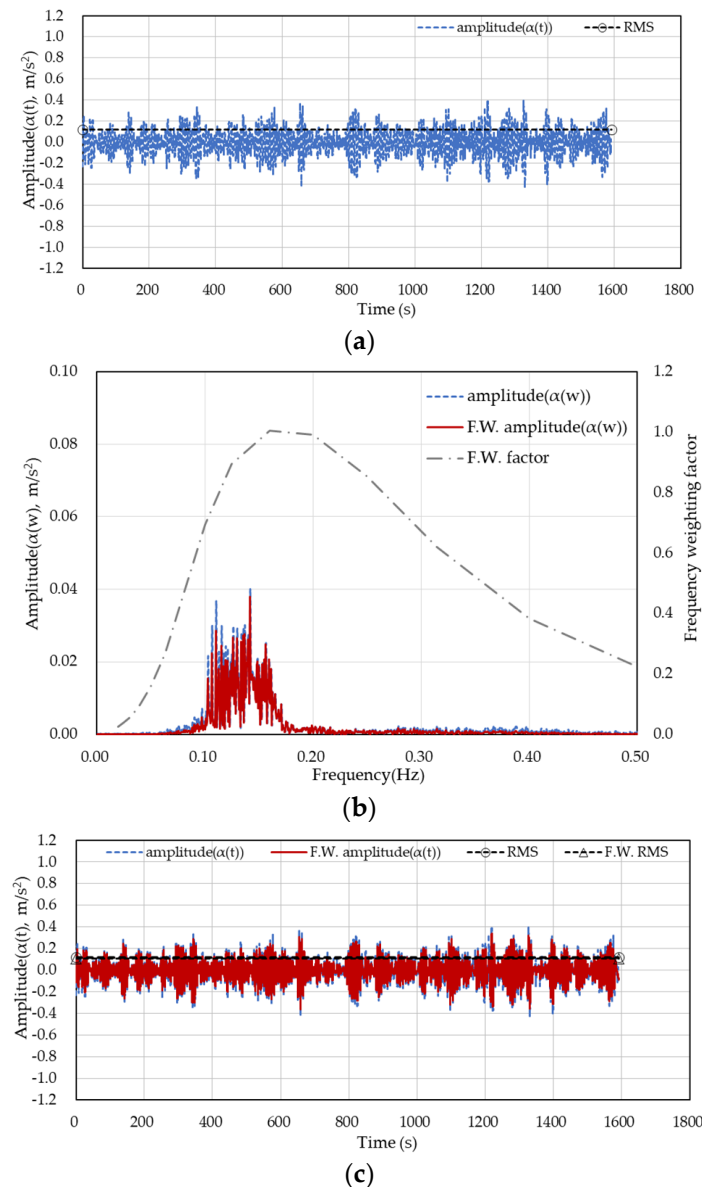


Figure 12. RMS acceleration of CASE 2-1 (1 yr.: $H_s = 1.3$ m, $T_p = 6.0$ s.): (a) Measured acceleration (blue line); (b) Response spectrum; (c) Frequency-weighted acceleration (red line).

(2) Inclination (angle)

For the CASE 1-1 test model, the time history of the inclination measured at the center of the test model for wave loads with 1-year and 100-year return periods is shown in Figure 14a and Table 6. For the 1-year return period wave load, the absolute maximum inclination was approximately 4.571° , and the RMS inclination was approximately 0.901° . For the 100-year return period wave load, the absolute maximum inclination was approximately 5.597° , and the RMS inclination was approximately 1.479° .

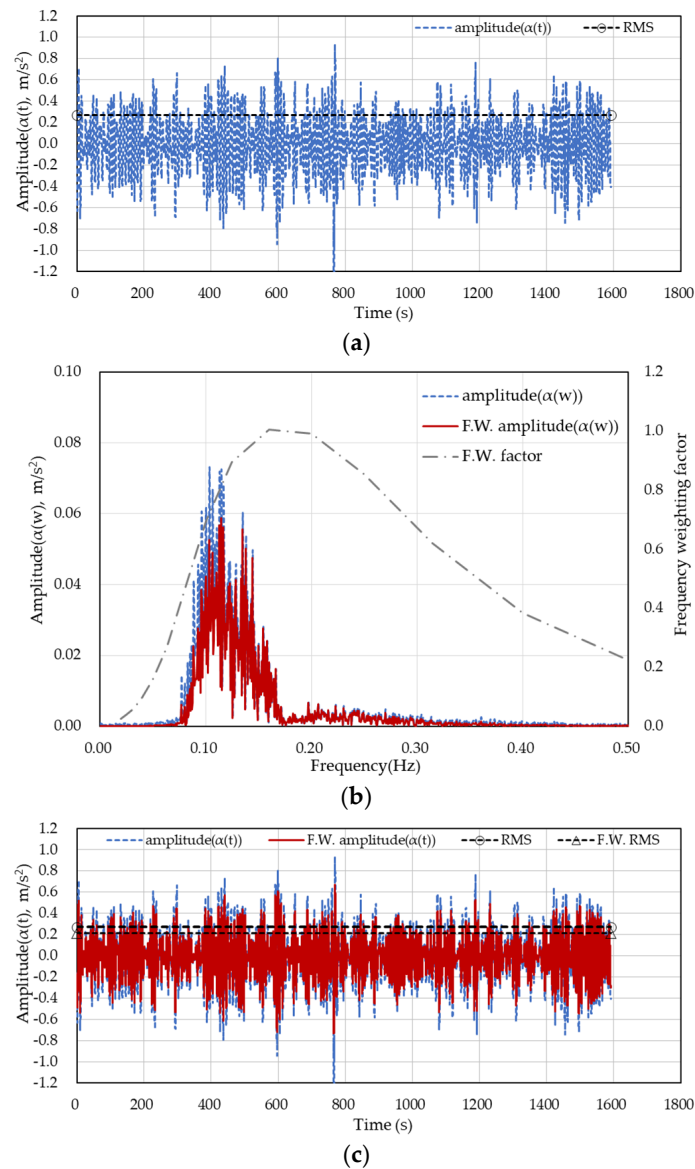


Figure 13. RMS acceleration of CASE 2-1(100 yr.: $H_s = 2.1$ m, $T_p = 8.0$ s.): (a) Measured acceleration (blue line); (b) Response spectrum; (c) Frequency-weighted acceleration (red line).

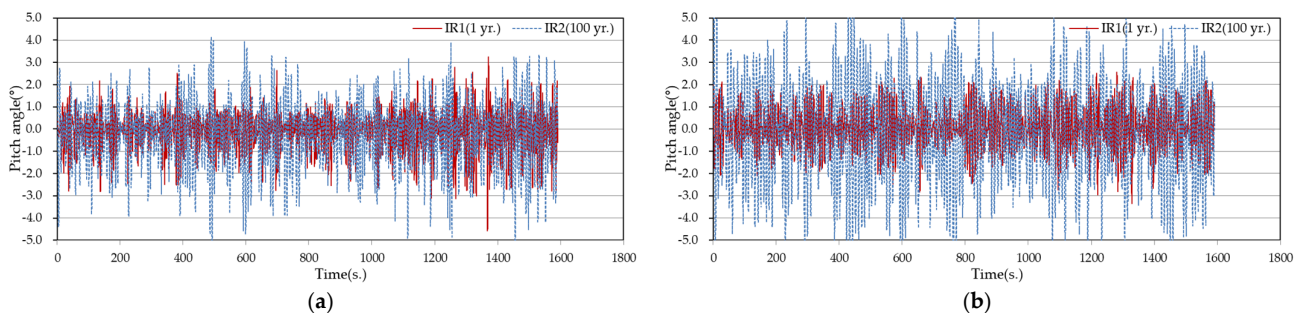


Figure 14. RMS inclination (angle): (a) CASE 1-1; (b) CASE 2-1.

For the CASE 2-1 test model, the time history of the inclination measured at the center of the test model for wave loads with 1-year and 100-year return periods is shown in Figure 14b and Table 6. For the 1-year return period wave load, the absolute maximum inclination was approximately 3.353° , and the RMS inclination was approximately 0.950° . For the 100-year return period wave load, the absolute maximum inclination was approximately 7.770° , and the RMS inclination was approximately 2.348° .

Table 6. Summary of RMS inclinations (angle) for prototype.

Items	1 yr. (Hs = 1.3 m, Tp = 6.0 s.)		100 yr. (Hs = 2.1 m, Tp = 8.0 s.)		Etc.
	CASE1-1	CASE2-1	CASE1-1	CASE2-1	
MAX	4.571	3.353	5.597	7.770	
RMS	0.901	0.950	1.479	2.348	
AVG	0.684	0.764	1.158	1.920	
RMS/AVG	1.32	1.24	1.28	1.22	

4.2. Enhanced Serviceability of Wave-Dissipating Modules

(1) RMS accelerations

The RMS accelerations of the floating structure with the wave-dissipating module were calculated in the same method as the prototype. The influence of the wave-dissipating module on the RMS acceleration of the floating structure was analyzed for wave loads with 1-year and 100-year return periods, and the results are presented in Tables 7 and 8, respectively. The analysis results for the RMS accelerations for the 1-year return period wave load indicated that, with the wave-dissipating module, CASE 1 series (only floating structure) showed approximately 44~45% levels of the prototype's RMS acceleration, and CASE 2 series (floating structure with topside) showed approximately 64% level. For the 100-year return period wave load, the RMS acceleration with the wave-dissipating module for CASE 1 series was approximately 54~57% levels of the prototype, and for CASE 2 series, it was approximately 63~64% levels.

Table 7. Reduction of RMS acceleration due to wave-dissipating module: 1 yr.

Items	CASE 1 Series				CASE 2 Series			
	RMS acc. A		RMS acc. B		RMS acc. A		RMS acc. B	
	CASE 1-1	CASE 1-2	CASE 1-1	CASE 1-2	CASE 2-1	CASE 2-2	CASE 2-1	CASE 2-2
MAX	1.018	0.317	0.835	0.282	0.428	0.269	0.361	0.220
RMS	0.224	0.101	0.212	0.093	0.119	0.076	0.107	0.068
	-	(0.45)	-	(0.44)	-	(0.64)	-	(0.64)
AVG	0.172	0.079	0.164	0.073	0.094	0.061	0.084	0.055
RMS/AVG	1.30	1.27	1.29	1.26	1.27	1.25	1.27	1.25

Table 8. Reduction of RMS acceleration due to wave-dissipating module: 100 yr.

Items	CASE 1 Series				CASE 2 Series			
	RMS Acc. A		RMS Acc. B		RMS Acc. A		RMS Acc. B	
	CASE 1-1	CASE 1-2	CASE 1-1	CASE 1-2	CASE 2-1	CASE 2-2	CASE 2-1	CASE 2-2
MAX	1.615	0.746	1.086	0.513	1.491	0.578	0.729	0.424
RMS	0.352	0.202	0.315	0.169	0.271	0.172	0.217	0.136
	-	(0.57)	-	(0.54)	-	(0.64)	-	(0.63)
AVG	0.282	0.165	0.253	0.139	0.219	0.140	0.175	0.110
RMS/AVG	1.25	1.22	1.24	1.22	1.24	1.23	1.24	1.23

This is clearly distinguishable in the response spectrum (irregular wave) of the vertical acceleration of the floating structure shown in Figure 15 and the response time history (regular waves) shown in Figure 16. The effect of reducing RMS acceleration results in improved serviceability concerning the vertical acceleration of the prototype of floating structure.

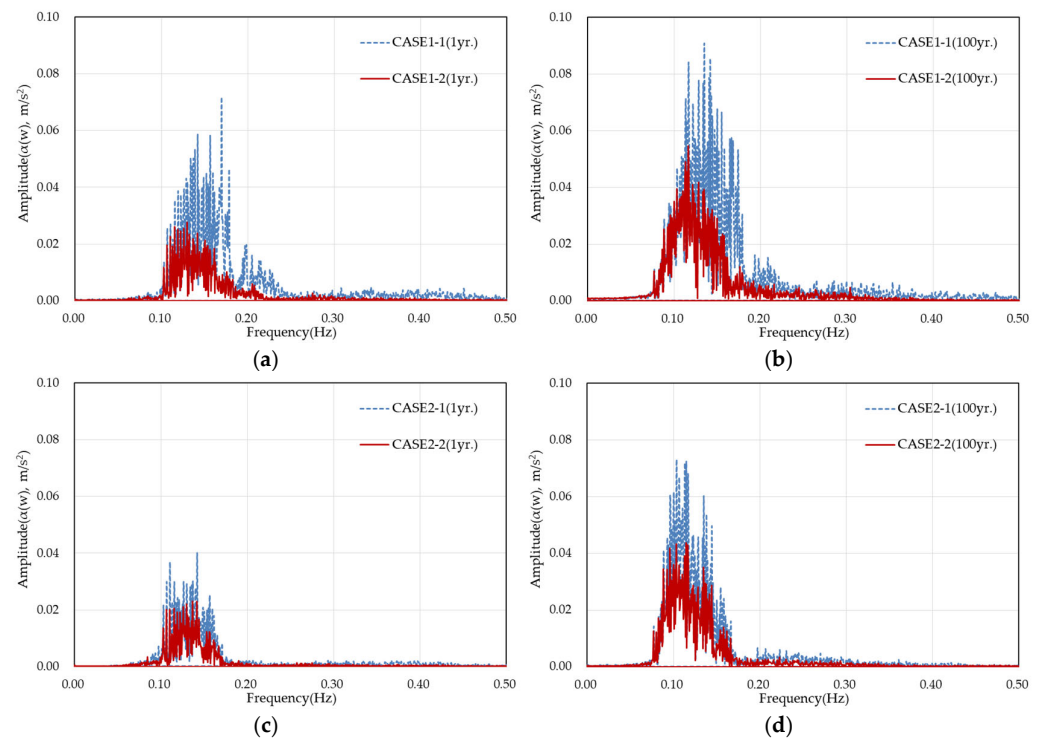


Figure 15. Response spectra due to wave-dissipating module under irregular wave: (a) CASE 1 series (1 yr.); (b) CASE 1 series (100 yr.); (c) CASE 2 series (1 yr.); (d) CASE 2 series (100 yr.).

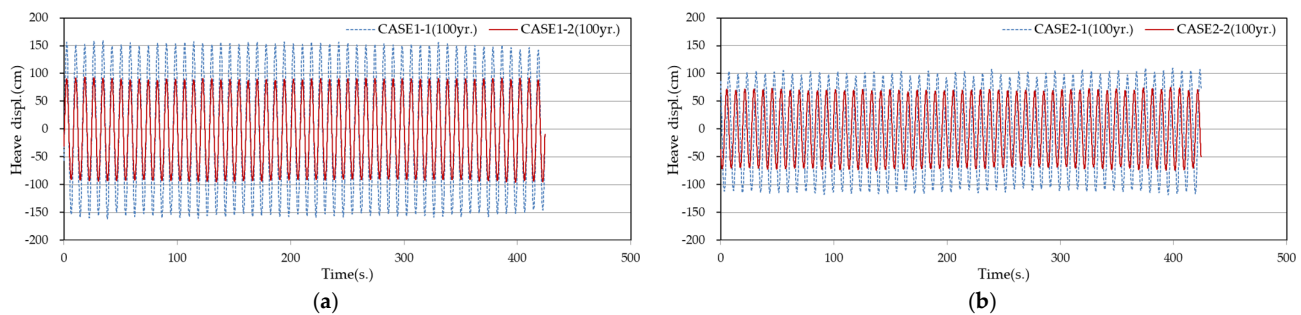


Figure 16. Response time history due to wave-dissipating module under regular wave: (a) CASE 1 series (100 yr.); (b) CASE 2 series (100 yr.).

(2) Inclination (angle)

The RMS inclinations of the floating structure with the wave-dissipating module were calculated in the same method as the prototype. The influence of the wave-dissipating module on the RMS inclination of the floating structure was analyzed for wave loads with 1-year and 100-year return periods, and the results are presented in Figure 17 and Table 9. The analysis results for the RMS inclinations for the 1-year return period wave load indicated that, with the wave-dissipating module, CASE 1 series showed approximately 55% level of the prototype's RMS inclination, and CASE 2 series showed approximately 66% level. For the 100-year return period wave load, the RMS inclination with the wave-dissipating module for CASE 1 series was approximately 77% level of the prototype, and for CASE 2 series, it was approximately 67% level.

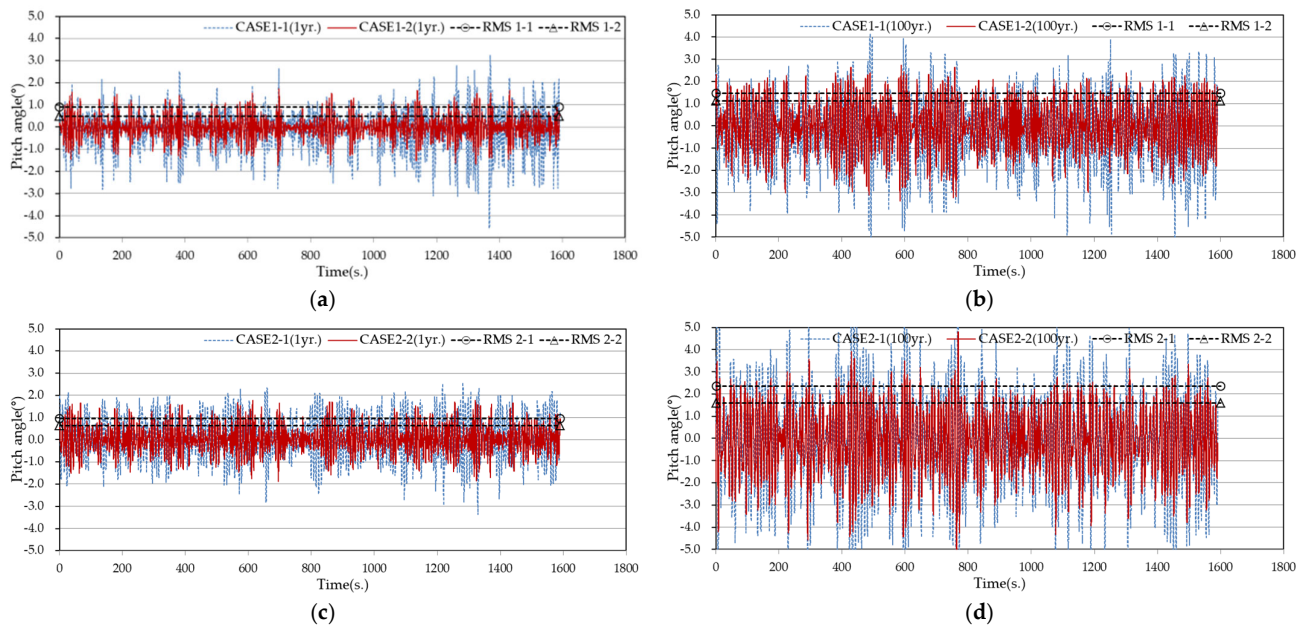


Figure 17. RMS inclination (angle) due to wave-dissipating module: (a) CASE 1 series (1 yr.); (b) CASE 1 series (100 yr.); (c) CASE 2 series (1 yr.); (d) CASE 2 series (100 yr.).

Table 9. Reduction of RMS inclination (angle) due to wave-dissipating module.

Items	CASE 1 Series				CASE 2 Series			
	1 yr.		100 yr.		1 yr.		100 yr.	
	CASE 1-1	CASE 1-2	CASE 1-1	CASE 1-2	CASE 2-1	CASE 2-2	CASE 2-1	CASE 2-2
MAX	4.571	1.728	5.597	3.386	3.353	1.877	7.770	5.438
RMS	0.901	0.496 (0.55)	1.479	1.138 (0.77)	0.950	0.624 (0.66)	2.348	1.580 (0.67)
AVG	0.684	0.371	1.158	0.934	0.764	0.495	1.920	1.320
RMS/AVG	1.32	1.34	1.28	1.22	1.24	1.26	1.22	1.20

(3) Topside (additional weight) effects

The serviceability evaluation was conducted at the bow (front). In the case of regular waves, as shown in Figure 16, the heave displacement at the bow of the CASE 2 series was smaller than that of the CASE 1 series. This is considered to be due to the heavier weight effect of the CASE 2 series, resulting in reduced motion. However, in the case of irregular waves, as shown in Figure 17, the pitch angle of the CASE 2 series was larger than that of the CASE 1 series. This is because the bow receives the impact force of peak waves directly, and in the case of irregular waves, the dynamic inertial force effect due to the heavier weight and higher center of gravity of the CASE 2 series is significant.

In terms of the floating body's motion period, as shown in Figure 15, the period (s.) of the CASE 2 series in irregular waves was slightly longer (the frequency (Hz) was shorter) due to the weight effect compared to the CASE 1 series. Therefore, even though the pitch angle (heave displacement) of the CASE 2 series increases, the acceleration is more sensitive to the period (s.) change (m/s^2), and the increased period (s.) results in a tendency for the acceleration to decrease compared to the CASE 1 series.

5. Conclusions

This paper presents an experimental evaluation of the serviceability of floating structures designed for marine cities. The authors propose enhancing serviceability by incorporating wave-dissipating modules on the structure's periphery to reduce motion. The study uses small-scale model tests in a wave flume to compare the serviceability of structures with and without these modules under different wave conditions (1-year and 100-year return period waves). Serviceability is assessed using two key indicators: vertical acceleration (related to human comfort) and inclination (angle) (related to the stability of topside building).

The results of this study show that wave-dissipating modules significantly reduce vertical acceleration. The modules effectively dampen wave motion, leading to a substantial decrease in vertical acceleration. The reduction was approximately 44~45% levels for the prototype of the floating structure under 1-year return period waves and 54~57% levels for the 100-year return period waves. The reduction was similarly pronounced when the topside building was included, reaching 64% and 63~64% levels reduction under 1-year and 100-year return period waves, respectively. The wave-dissipating modules also mitigated inclination (angle), although the improvement was less dramatic than the reduction in vertical acceleration. Reduction rates ranged from 55~77% levels depending on the wave conditions and whether a topside building was present.

The experimental results demonstrate that incorporating wave-dissipating modules around the periphery of floating structures is an effective method for enhancing their serviceability. The significant reduction in vertical acceleration and improvement in inclination (angle) strongly suggest that these modules can create more comfortable and stable environments for human activities on floating offshore structures, while also enhancing the stability of the structure itself. The fundamental concept of the wave-dissipation modules of this study is to be attached to multi-sides of the floating body to respond to the multi-directionality of waves. However, in this experimental study, to primarily verify the unidirectional behavior of the floating body with the wave-dissipation modules, the modules were attached only to the bow (front) and stern (rear) sides of the floating body to suit the 2D wave flume test. Therefore, it is expected that the behavior of the actual floating body with the modules installed on multi-sides will differ, and this will be verified through additional experiments in the near future. Also, further research might focus on scaling up the model tests and conducting field experiments to validate these findings under real conditions. Optimization of module design for different wave conditions and structural configurations is also a potential area for future study.

Author Contributions: Conceptualization, Y.-J.J.; methodology, Y.-J.J. and J.K.; validation, Y.-J.J. and J.K.; formal analysis, Y.-J.J.; investigation, M.-S.P. and Y.-T.K.; resources, M.-S.P. and Y.-T.K.; data curation, M.-S.P. and Y.-T.K.; writing—original draft preparation, Y.-J.J.; writing—review and editing, Y.-J.J.; visualization, Y.-J.J.; supervision, Y.-J.J.; project administration, Y.-J.J.; funding acquisition, Y.-J.J. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure, and Transport (Grant RS-2023-00250727) through the Korea Floating Infrastructure Research Center at Seoul National University.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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