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URBAN DEVLOPMENT ON MODULAR FLOATING STRUCTURES FOR DISASTER MITIGATION IN COASTAL CITIES

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Abstract

Coastal areas are earthquake-prone zones where giant ruptures have been materialized throughout history. Coastal areas are also the first line of impact in a Tsunami event. Today when 40% of the global population (2.4 billion) live in coastal communities the threat for either disaster or both is imminent. This study offers an alternative approach to address coastal cities resilience to seismic shocks and Tsunamis, by the employment of modular floating structures (MFS), which can be utilized for urban development in the adjacent marine environment. The MFS concept is based on modular floating units, consolidated into a large structure to provides an adequate surface for mixed-use urban development. Floating structures are inherently base isolated; therefore, seismic loads are not transmitted to the structure foundation. This principle was tested successfully during the 1995 Great Hanshin Earthquake where the floating Kobe City Air Terminal (K-CAT) suffered no damage. In addition, Tokyo Bay, Osaka Bay and Ise Bay are all equipped with emergency floating platforms for evacuation in case of disaster. Which raise the query as to why not use floating platforms for urban development in pre-disaster condition? The design of MFS is an interdisciplinary endeavor, which encompass by few disciplines, mainly: architecture, naval architecture and civil engineering. Building a viable urban development on floating structures can help mitigate, or even eliminate, the disastrous effects of Tsunami, which accumulates into a destructive order only when approaching the shore. The hypothesis is that floating structures can offer a unique avenue to explore new and sustainable ways to mitigate structural damaged related directly to earthquake and/or Tsunami. This study examines the potential urban development and dwelling solutions for three mega-coastal-cities, such as Jakarta, Tokyo and Manila – all which are susceptible to major earthquakes. The study presents a feasibility model for an MFS preliminary design. The limit service state is achieved by implementing international regulations from a coherent statutorily guidelines, that are merged to fulfil the requirements for the special context of urban floating structures. The service limit state is achieved by extensive hydrodynamic analysis that evaluates the compatibility to occupant comfort acceptable in residential buildings.

Keywords: Disaster-mitigation; Floating-structures; Urban-development; Hydrodynamics; Regulations, Safety

1. Introduction

Floating structures and infrastructures offers a unique alternative to explore new sustainable ways to solve or mitigate some of the major issues in the resilience of coastal cities. This includes the tension between population growth and land scarcity, climate change related events (e.g. groundwater and sea level rise), the evermore frequent storm surges, all the way to disasters mitigation (mainly tsunami and earthquakes). These issues are within the global consent, as nearly 40% of the world's population lives in coastal-communities [1–5]. Thus far, land reclamation has been the common method for coastal expansion to the marine environment. However it is a destructive and wasteful method that recently became obsolete in many developed countries [6,7]. In the short term, land reclamation can create additional land, but it cannot adapt, in a sustainable way, to the inevitable issues of sea level rise. Furthermore, buildings constructed on land reclamation are not protected from seismic shocks [8,9].

In the last three decades the emerged alternative for land reclamation has been floating islands, known also as Mega-floats or Very Large Floating Structures (VLFS) [10–15]. Floating islands were portrayed as the sustainable solution for land reclamation, but evidently, have yet to fulfill their promise. The reasons for that may be related to production complexity, environmental effects (shading as result of its large static footprint), or economic viability. But furthermore, Mega-floats are typically designed for a particular purpose (e.g. airport, storage facility etc.) and are not considered a feasible alternative for urban development. The MFS concept solves all these issues, using smaller size (ship sizes) rigid modules to create a large scale, consolidated and permeable platform, for urban development offshore. These floating modules can be designed ad-hoc for any urban purpose (e.g. residential, recreational facilities, parks, etc.), and can be arranged, and rearranged in numerous spatial configurations [16].

The idea of urban development offshore has been rehashed in the conceptual world of architects and town planners for decades [17–22]. However, these utopian plans have never evolved into a complete realistic program due to the lack of equally pragmatic engineering research to help realize them towards feasible application. This research has proven the feasibility of the MFS concept from a structural and technological point of view. To close the gap of knowledge, a multi-disciplinary research approach was chosen, which included the relevant aspects of Naval Architecture, Marine Engineering, Civil Engineering and Architecture and Town Planning [23].

The research main unit of analysis is divided into three main aspects which hypothesizes a comprehensive proof of concept for MFS. The first aspect reconciles international regulations and building codes from both civil engineering and naval architecture to coherent statutorily guidelines in the special context of offshore dwellings, proving the MFS concept feasibility for actual applications [16]. The second aspect, through an extensive hydrodynamic analysis, evaluates the compatibility of the MFS modules to occupant comfort criteria acceptable in residential buildings onshore. This included a novel occupant comfort-based design methodology and assessment procedure in the frequency domain [24]. Increasing the allowable significant wave height, by efficient multibody configuration is the task of the third aspect. For the selected modules configuration, the analysis had shown great promise in mild sea zone; wavelength of 7 seconds and significant wave height < 2.0 m. At longer wave periods the MFS should be planned with breakwaters – conventional or floating.

This paper concisely examines the compatibility of the MFS design to the environmental condition in Tokyo bay area, and present an alternative suburb which is protected from seismic events. The paper outlines the methodology principals and the design phases required for preliminary design. This also includes theoretical background that closes the gap between the none linear problem of wave and structure and classic dynamics of structures using the equation of motion [25]. This is manifested in the results, where the free body hydrodynamic analysis is converted to RMS accelerations to comply with residential buildings comfort criteria.

2. Design approach and methodology

This section reviews the conceptual and preliminary design process for the MFS concept. The design of an MFS module is based on two principal phases: ultimate limit state and service limit state design. The first phase examines the hydrostatic stability of the chosen dimensions, i.e. matching the floating platform to the desired superstructure. This is done in full compliance to safety regulations under the auspices of the International Maritime Organization (IMO). This includes the structural response of the floating platform in both the longitudinal (still water and wave bending moments) and the transverse conditions (in the case of rigid multi hulls). These regulations are mainly related to the period when the modules are transported and operates as a vessel, special service craft, or barge in open water, however without the live load (passengers /residents). The second phase focuses on the motion characteristics (hydrodynamics) of the module and habitability during its stationary service years as building unit in MFS platform. These regulations are mainly related to occupant comfort and safety of the passengers /residents.

The principal design system used to calculate the MFS modules, and to prove its feasibility for offshore dwelling and as additional urban space, is given in the subsections below:

2.1 Input 1: Ultimate limit state design – Transport

2.1.1 Design main particulars (substructure and superstructures dimension).

2.1.2 Hydrostatic and structural analyses.

2.1.3 Regulation (using the merged requirements of the Common Rule Approach [16])

Not successfully complying to the given regulations, will start a new iteration. The modifications in the next iteration (back to the design main particulars) can be made either to the substructure or the superstructure, or both. Changing the superstructure (e.g. height, spatial sizing, or structural material) influences both stability (through the position of the vertical center of gravity) and loading conditions. The changes to the substructure can influence the stability for the better, by increasing its beam, or make in worse by increasing its draft (mainly to large angles of heel).

2.2 Input 2: Service limit state design – Stationary

2.2.1 Environmental conditions: waves, wind and current.

2.2.2 Hydrodynamic analysis.

2.2.2.1 Frequency domain (occupant comfort)

2.2.2.2 Time domain (drift forces and fastening calculations)

2.2.3 Regulations (comfort criteria in residential buildings)

In this case the input denotes the specific environmental conditions for the stipulated venue (e.g. Tokyo, Jakarta, or Manila). This input is used to determine the occupant comfort condition and the habitability of the planed MFS. The entire range of incident wave periods are considered in the frequency domain analysis, which expose the areas were the modules endure most extreme oscillations. In case this accrues in operational weather conditions we can either increase the module size, or change the environmental conditions using breakwaters. The time domain analysis is used to calculate the second order drift forces, that are used for the design of the mooring system, and the motion response in nonlinear wave structure interaction, if constraints are implemented. The outputs of the two analyses (linear and nonlinear) are given in Fig. 1 and Fig. 2.

Understanding that satisfying the legal building requirements of the modules does not mean that this concept will be successful. The dynamic response of the modules may cause discomfort to some, and fear and alarm to others, even though they are safe. Hence it is crucial to emphasis on the dynamic response and mitigated it to assure comfort compliance during service conditions. Building the MFS modules in the size of conventional ocean-going vessels enables the use of regulations, codes, classifications and even insurance, making this utopian concept realistic.

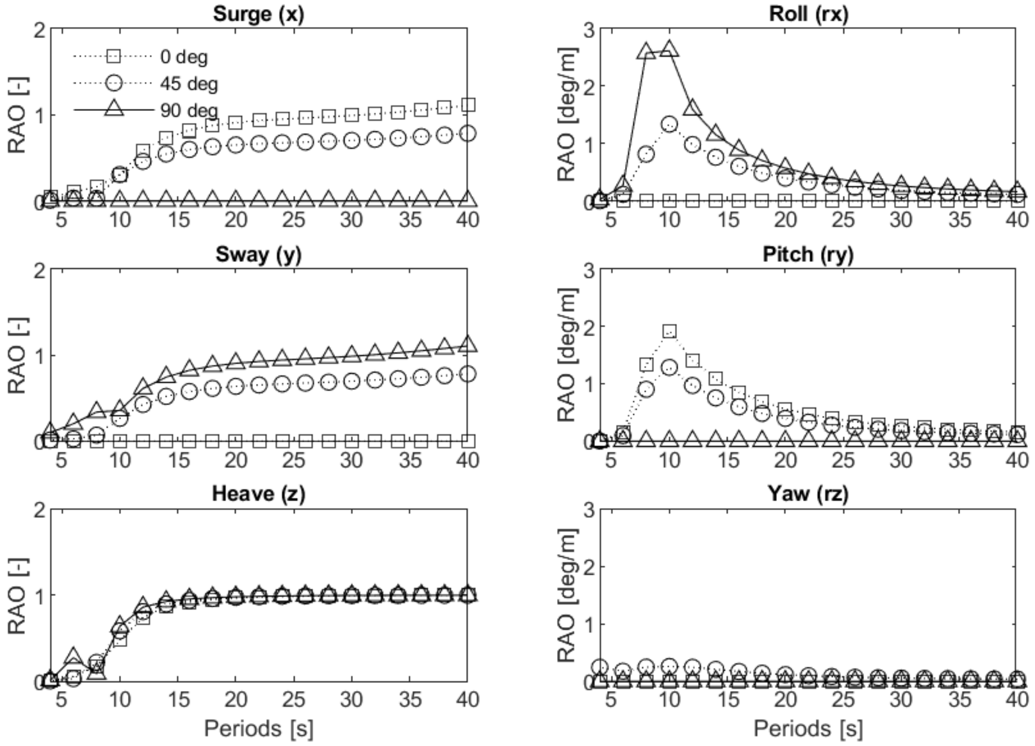

Fig. 1 – Linear Response Amplitude Operators (RAOs)

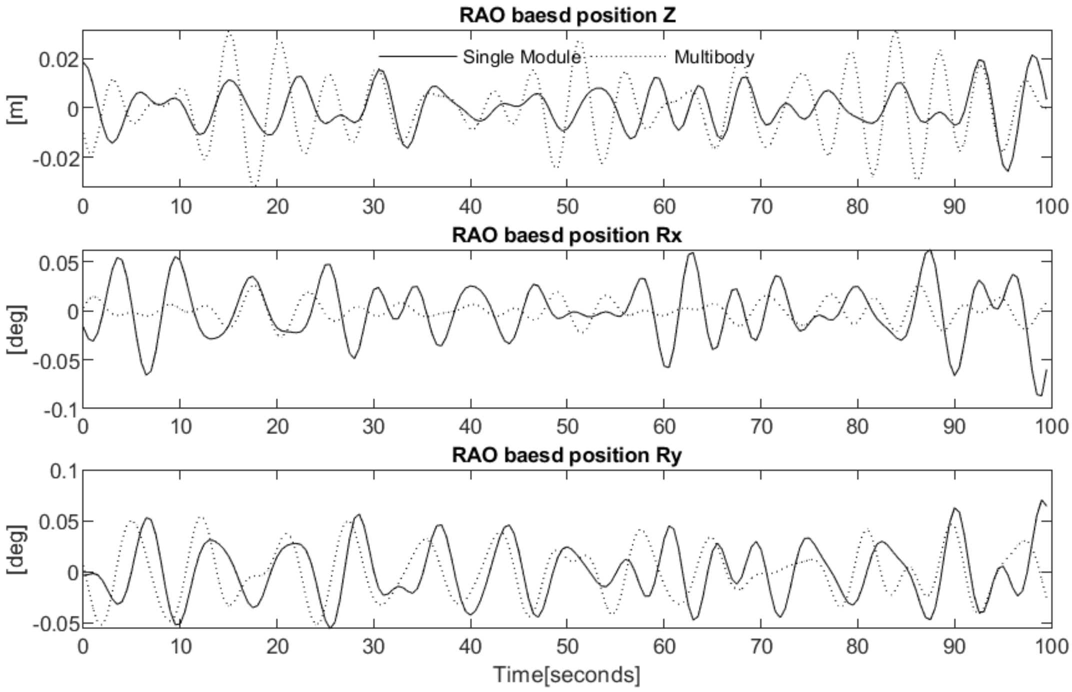

Fig. 2 – Nonlinear time series

3. Theoretical background

The hydrodynamic calculations are performed with ANSYS-AQWA analysis system.

3.1 Mathematical formulation

Formulating the nonlinear problem of wave structure interaction, using the equation of continuity Eq. (1), where Φ is defined so that the ∇Φ is the flow velocity. The associated boundary conditions for the equation of continuity is following in the subsections below, Eq. (2-7).

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

3.1.1 Seabed condition, where h is the water depth (at water plane h=0)

$$\frac{\partial\Phi}{\partial z} = 0, \qquad at\ z = -h \tag{2}$$

3.1.2 Wetted Surface condition of the water surface area of the considered modules. Where V is the body's velocity vector and n is a unit vector normal to the wetted surface (S_B).

$$\frac{\partial\Phi}{\partial n} = \bar{V} \cdot \bar{n}, \qquad at\ S_B(t) \tag{3}$$

3.1.3 Kinematic free surface condition.

$$\frac{\partial\eta}{\partial t} + \frac{\partial\Phi}{\partial x} \cdot \frac{\partial\eta}{\partial x} + \frac{\partial\Phi}{\partial y} \cdot \frac{\partial\eta}{\partial y} - \frac{\partial\Phi}{\partial z} = 0, \qquad z = \eta(x, y, t) \tag{4}$$

3.1.4 Dynamic free surface condition. Where $\eta(x, y, t)$ the free (water) surface function so that $z - \eta = 0$.

$$\frac{\partial\Phi}{\partial t} \cdot \frac{1}{2}\nabla\Phi \cdot \nabla\Phi + g \cdot \eta = 0, \qquad z = \eta(x, y, t) \tag{5}$$

3.1.5 Radiation condition.

For small wave steepness the problem may be linearized by expansion of the potential (Φ) and water surface (η) functions follows in Eq. (6-7). The wave steepness (the product of the wave number and amplitude) is given as ε.

$$\Phi = \varepsilon\Phi^{(1)} + \varepsilon^2\Phi^{(2)} + \cdots \tag{6}$$

$$\eta = \varepsilon\eta^{(1)} + \varepsilon^2\eta^{(2)} + \cdots \tag{7}$$

3.2 First order solution (linear and monochromatic).

The potential function Φ can be written as given in Eq. (8), where ϕ is complex space depended part of the potential function. In Eq. (9) the ϕ is separated into incident wave potential, diffracted wave potential, and the potential functions of the radiated waves in six degrees of freedom. Formulation of the first order linear problem denotes also the following relations for the incident and diffraction potentials, as given in Eq. (10), and Eq. (11). The continuity equation (Laplace) is given in Eq. (12).

$$\Phi = (\mathrm{X}, \mathrm{Y}, \mathrm{Z}, \mathrm{t}) = Re[\phi(X, Y, Z)e^{-i\omega t}] \tag{8}$$

$$\phi(X, Y, Z) = (\phi_i + \phi_d) + \sum_{j=1}^{6} \phi_j x_j \tag{9}$$

$$\phi_i = \phi_0, \qquad \phi_j = \phi_j, \qquad j = 1, \dots, 6 \tag{10}$$

$$\phi_d = \phi_j, \qquad \phi_j = \phi_j, \qquad j = 7 \tag{11}$$

$$\nabla^2\phi_j = 0, \qquad \mathrm{j} = 1, \dots, 7 \tag{12}$$

The boundary condition Eq. (2-7), can be rewritten with respect to j.

The solution employed by ANSYS-AQWA, for the diffracted and radiated wave potentials $(\phi_i + \phi_d)$

The solution of the first order linear problem used by the analysis system ANSYS=AQWA is written in Eq. 13,

$$\phi_i = \frac{iga_w \cosh[k(h+z)]e^{i[k(x\,cos\beta + y\,sin\beta)]}}{\cosh(kh)} \tag{13}$$

$$\omega^2 = gk \tanh(kh) \tag{14}$$

Where, Z is the vertical coordinate measured to the water plane; h is the water depth; g is the gravitational acceleration; H is the wave height; k is the wave number (Eq. (14)); ω is the wave angular frequency; β is the wave direction, and a_w is the wave amplitude

The solution employed by ANSYS-AQWA, for the diffracted and radiated wave potentials $(\phi_i + \phi_d)$ is pulsating source distribution – numerical method that is based on the Green's function. Once the velocity potentials are known the first order pressure can be calculated as given in Eq. (15). Integrated value of the pressure along the wetted surface area of the module, provides the applied fluid force on the floating structure (Fj) as given in Eq. 16, and Eq. 17. The forces are separated into Foude-Krylov (F_{ij}), diffraction forces (F_{dj}), and radiation forces (F_{rjk}). The radiation force F_{rjk} is given in in Eq. (18),where, A_{jk} is the added mass coefficient and B_{jk} is damping confident.

$$P^{(1)} = -\rho\frac{\partial\Phi}{\partial t} = i\omega\rho\phi(\bar{X})e^{-i\omega t} \tag{15}$$

$$F_j(\bar{X}) = i\omega\rho\int \phi(\bar{X})n_j ds \tag{16}$$

$$F_j = [(F_{ij} + F_{dj}) + \sum_{k=1}^{6} F_{rjk}\, x_k]\,,\;\; j = 1, \dots, 6 \tag{17}$$

$$\begin{aligned} F_{rjk} &= -i\omega\rho\int \{Re[\phi_{rk}(\bar{X})] + iIm[\phi_{rk}(\bar{X})]\}\, n_j ds \\ &= \omega^2 A_{jk} + i\omega B_{jk} \end{aligned} \tag{18}$$

3.3 Equation of motion and the Response Amplitude Operator (RAO).

$$[-\omega^2(M_s \cdot + M_A(\omega)) - i\omega C(\omega) \cdot + K_s] \cdot X(\omega) = F(\omega) \tag{19}$$

Based on the Equation of Motion presented in, the Response Amplitude Operator (RAOs), indicated as X, can be calculated, when writing, $X = X_0 e^{-i\omega t}$, and $F = F_0 e^{-i\omega t}$. Where, *M*$_s$ is the structural mass matrix of the chosen module, *M*$_A$ is hydrodynamic added mass matrix, *C* is the linear damping matrix, *K* is the stiffness matrix, *X* is the response motions (RAO), and *F* is the external wave force.

4. Results

The analysis shows the results of the hydrodynamic examination for a given MFS configuration positioned in Tokyo Bay area. The schematic layout of an MFS is presented in Fig. 4. This was published in an earlier study [16], and is given here for reference purposes only. The MFS analysis model is constructed from all equal modules. The module size is100 meter long and 75 meter in beam, and they are assumed rigid. Each module is constructed from two hulls (catamaran) with 15-meter clearance between them, and accommodates 6 building with 10 floors. The analysis can be given about the center of gravity or to any other point specified. ANSYS-AQWA is able to perform a full hydrodynamic interaction that includes radiation coupling and shielding effects for up to 20 structures, as presented in the wave/module interaction given in Fig. 4. The hydrodynamic model is presented in Fig. 5.

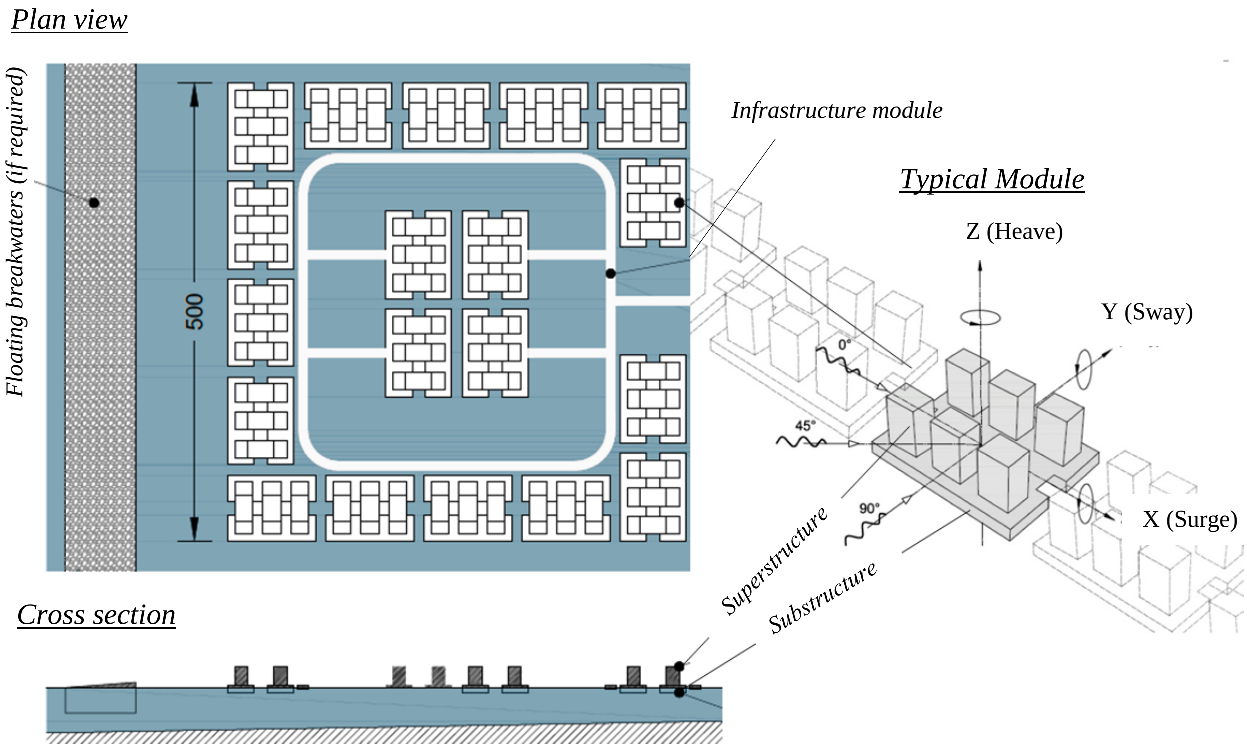

Fig. 3 – Schematic MFS layout, a neighborhood of 2280 apartments, each of 140 m^2 Ref. [16]

The calculated RAOs (Eq. (19)) presents the motion response to regular waves (monochromatic). This data can be transformed to irregular waves using the JONSWAP (Joint North Sea Wave Project) spectrum to describe real sea, or irregular-sea. The real sea representation is given by the root mean square (RMS) for all the degrees of freedoms motions, as a function of the significant wave heights at the selected venue. The RMS values can be obtained by integrating the JONSWAP spectrum $S(f)$, and multiply it by the corresponding squared RAO, as given in Eq. (20) [26].

$$RMS = \sqrt{\int RAO^2(f) \cdot S(f)\, df} \tag{20}$$

Having calculated the actual real sea amplitude per wave frequency we can than convert them into accelerations to find if structural motion complies to the acceptable residential building standards in term of occupant comfort. Heave, Roll and Pitch are the degrees of freedom most associated with occupant comfort due to their vertical oscillations.

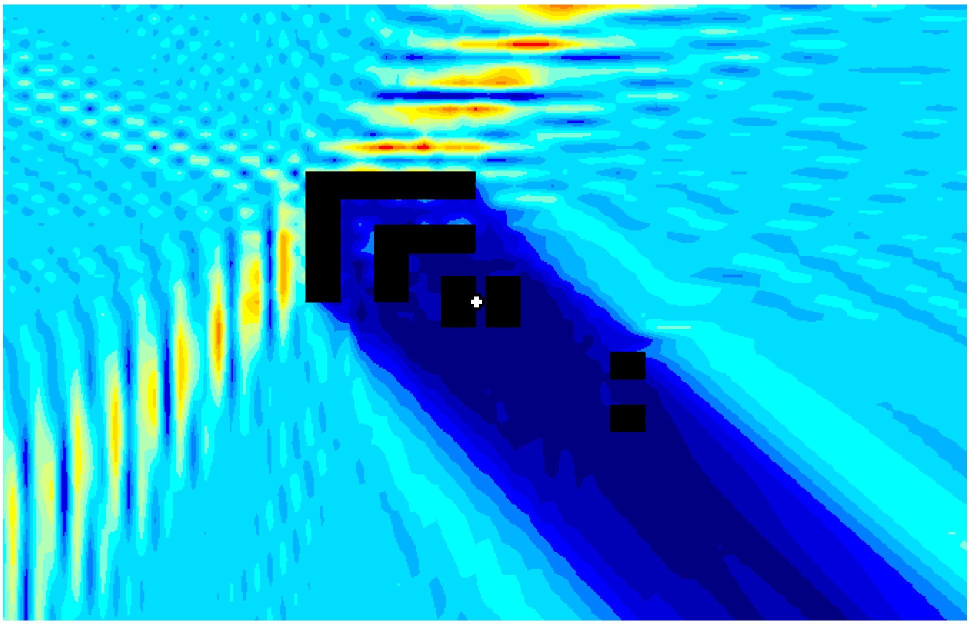

Fig. 4 – Waves / modules interaction (hydrodynamics) in 45° waves heading

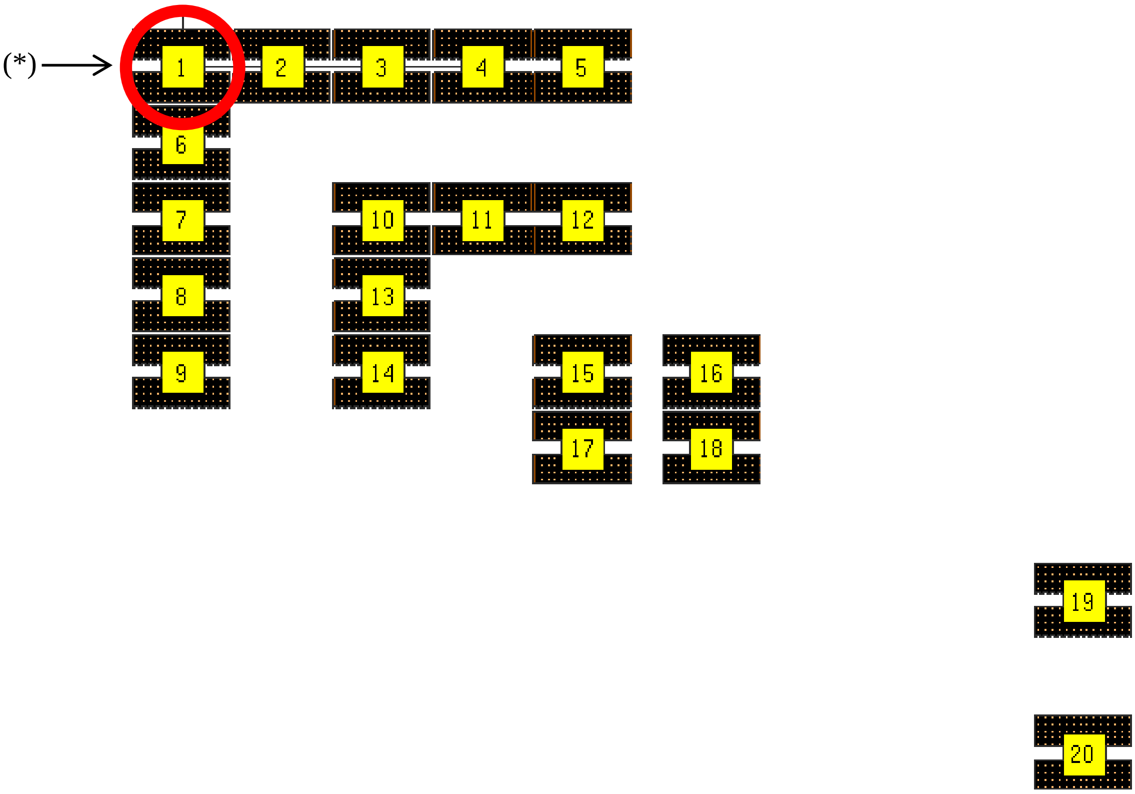

Fig. 5 – Close-up on the hydrocyanic model

(*) All the presented results hereafter (Fig. 6, Fig. 7, and Fig. 8) are given with respect to center of gravity of module 1. Since this is the module directly facing the incident waves, and will have the largest motion amplitudes. Providing its hydrodynamic behavior, and calculating its compliance to occupant comfort, is assumed to be more conservative approach, as the leeward modules (e.g. 10, 15, and 20) are shielded by the outer modules in the MFS and will perform better in terms of occupant comfort. The wave statistics in Tokyo Bay denotes that a storm wave height is about 1 meter and periods range between 2-6 seconds [27].

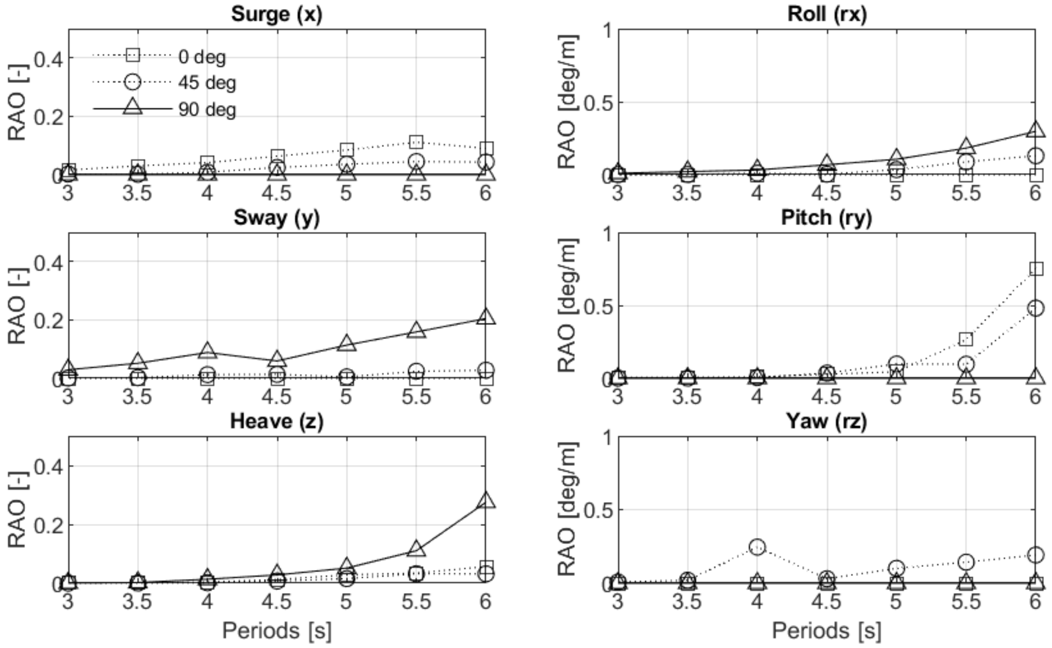

Fig. 6 – Calculated RAOs in Tokyo Bay for module number 1, following Ref. [24]

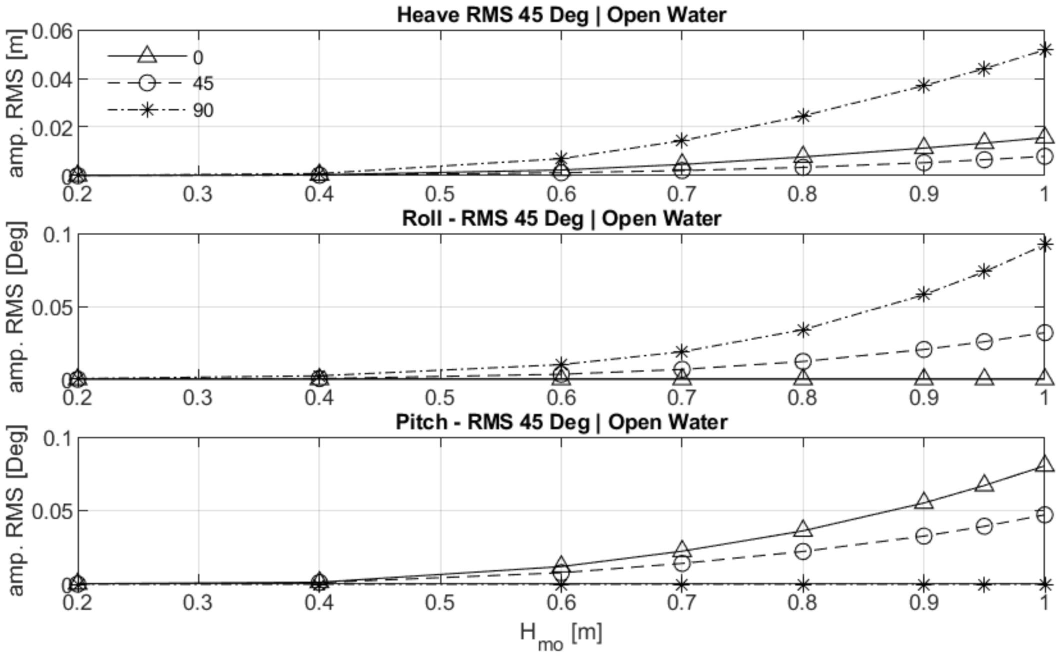

Fig. 7 – Real sea transformation for module number 1, following Ref. [24]

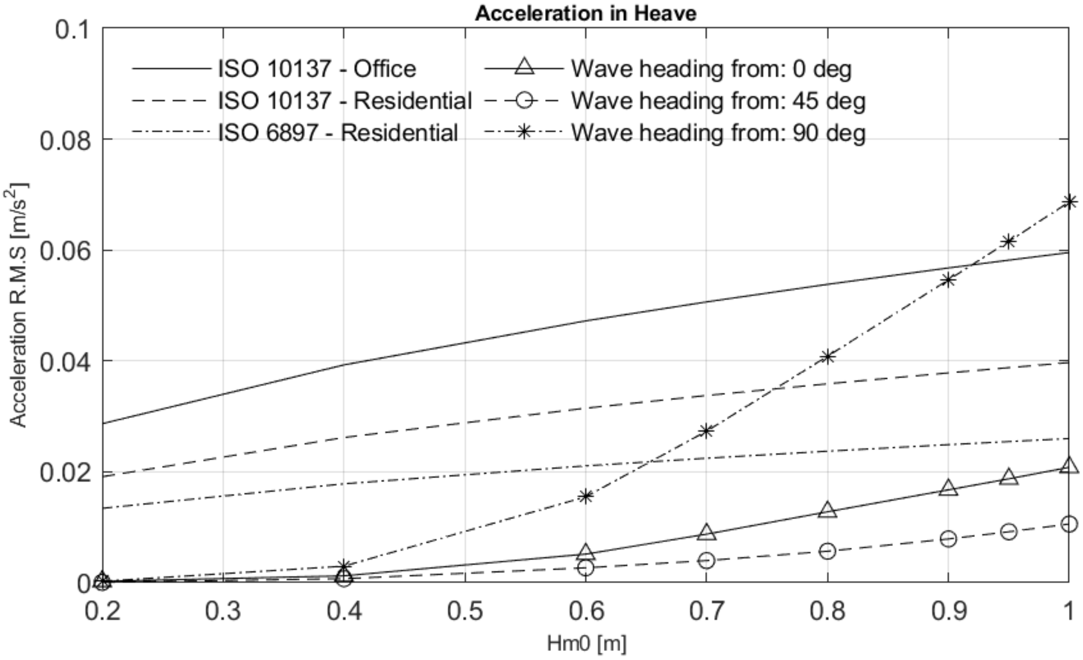

Fig. 8 – Occupant comfort criteria for module number 1 in Tokyo Bay, following Ref. [24]

5. Conclusions

The MFS concept is a technological adaption that can reduce the risks associated to both earthquakes and Tsunamis, particularly in the context of climate change and sea level rise. The environmental conditions – mainly the wave periods and heights, are key for designing the MFS modules with respect to occupant comfort. Fig. 8 shows the compliance of module 1 to the accepted comfort criteria in residential building. The output is given based on the wave statistics in Tokyo Bay area. In oblique and frontal waves (0° and 45°) the module is providing the required inherent motion stability for urban needs. At beam waves (90°) the comfort compliance is adequate until a certain wave length. This, in relation to the chosen parameters of the module. The bigger the module the better it can endure its motion stability at longer wave periods (assuming it has valid hydrostatics) or it can be positioned in such way to avoid beam waves.

To define the preliminary box parameters (length, beam and depth) of the modules substructure a range of existing ships and barges were examined together with shipyards size capacities. This had revealed that a key parameter or restriction for many of the commercial shipyards is either the draft, associated with the local water depth (slipways depth), or the beam, which is the maximal width of the fabrication hall. Yet, further investigation had shown that draft is not as crucial factor, as it can be managed using dedicated equipment (e.g. cranes and barges). The beam, on the other hand, is a limiting restrain, originated from the size of vessels permitted through Panama Canal. The channel’s max beam is 32 meters, and the Draft is 12 meters. These are principal dimensions, as most of the commercial shipyards today are capable of producing vessels within this box boundary. Exceeding either beam or draft, means that the production of the modules will not fit in most existing yards, consequently increasing the initial investment.

In the case of Tokyo Bay, with storm wave height about 1.0 meter and wave periods of 2-6 seconds the MFS module considered performs adequately as a single free floating module and as part of the consolidated MFS unit proposed.

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