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Hydroelastic analysis of pontoon-type VLFS: a literature survey

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Abstract

Presented herein is a literature survey of the research on hydroelastic analysis of pontoon-type very large floating structures (VLFS). After a brief introduction of VLFS, the reader is provided with the basic assumptions, equations and boundary conditions for a hydroelastic analysis of VLFS and the commonly used approaches for solving the problem. Based on a comprehensive search, research papers that contain significant contributions to the aforementioned topic are grouped under the following topics: wave forces, drift forces and other forces, VLFS models, VLFS shapes, mooring system, breakwaters, profiles of seabed, and anti-motion devices. More importantly, some future directions for VLFS research are articulated. In addition to providing a long list of papers, we also include a list of relevant conference proceedings, and websites containing valuable information on VLFSs.

Keywords: VLFS; Hydroelastic analysis; Plate models; Mooring facilities; Breakwaters; Profiles of seabed; Damper systems

1. Introduction

With a growing population and a corresponding expansion of urban development in land-scarce island countries and countries with long coastlines, the governments of these countries have resorted to land reclamation from the sea in order to ease the pressure on existing heavily-used land space. There are, however, constraints on land reclamation works, such as the negative environmental impact on the country's and neighbouring countries' coastlines and marine eco-system, as well as the huge economic costs in reclaiming land from deep coastal waters, especially when the sand for reclamation has to be bought at an exorbitant price. In response to both the aforementioned needs and problems, engineers have proposed the construction of very large floating structures (VLFS for short) for industrial space, airports, storage facilities and even habitation. Japan, for instance, have constructed the Mega-Float [1] (a VLFS test model for floating airport terminals and airstrips) in the Tokyo bay, the floating amusement facilities in the Hiroshima Prefecture, the Yumeshima-Maishima floating bridge in Osaka, the floating emergency rescue bases in Yokohoma, Tokyo and Osaka, and the floating oil storage systems in Shirashima and Kamigoto. Canada has built a floating heliport in Vancouver and the Kelowna floating bridge on Lake On in British Columbia. Norway has the Bergsoysund floating bridge and the Nordhordland bridge which has a floating portion, while the United States has the Lacey V. Murrow bridge and the Hood Canal floating bridge. Vietnam has a floating hotel. These VLFSs have advantages over the traditional land reclamation solution in the following respects: they are cost effective when the water depth is large; environmentally friendly as they do not damage the marine eco-system, or silt-up deep harbours or disrupt the ocean currents; they are easy and fast to construct and therefore sea-space can be speedily exploited; they can be easily removed or expanded; and the structures on VLFSs are protected from seismic shocks since the energy may be dissipated by the sea.

VLFSs may be classified under two broad categories, namely the pontoon-type and the semi-submersible type as shown in Fig. 1. The former type is a simple flat box structure and features high stability, low

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Mega-Float in Tokyo Bay   Aquapolis in Okinawa

Fig. 1. Pontoon-type VLFS and semi-submersible-type VLFS.

manufacturing cost and easy maintenance and repair. However, this pontoon-type of floating structure is only suitable for use in calm waters associated with naturally sheltered coastal formations. To further reduce the height of waves that impact on these pontoon-type VLFS, breakwaters are usually constructed nearby. In open seas where the wave heights are relatively large, it is necessary to use the semi-submersible type of VLFS to minimize the effects of waves while maintaining a constant buoyant force.

Since the pioneering work of John [2] on the motion of a floating rigid thin plane slab, there has been extensive research done on the analysis of very large floating structures. The numerous publications reported in offshore structures/VLFS conference proceedings, journals, books and websites bear testimony to the interest and importance of these structures to engineers and researchers. It is therefore timely to reflect on what has been done, what is currently been investigated and what future directions to proceed from hereon in a single document. Recently Kashiwagi [3] presented a review of recent studies on the prediction of hydroelastic responses of VLFS. Complementing Kashiwagi's work, this paper presents a more exhaustive survey on the research work on pontoon-type VLFSs (which has also been referred to in the literature as mat-like VLFSs because of the small draft in relation to the length dimensions). The pontoon-type/mat-like VLFS is very flexible when compared to other kinds of offshore structures and so the elastic deformations are more important than their rigid body motions. Thus, hydroelastic analysis takes centre stage in the analysis of mat-like VLFSs. Breakthrough works by Bishop and Price [4] and Price and Wu [5] led to the full 3-D hydroelasticity theory, where the Green function method is used to model the fluid and the finite element method to model the VLFS. In this survey paper, the authors first present the basic assumptions, equations and boundary conditions for a preliminary hydroelastic analysis of such VLFSs. Next, we review the papers that reported the development of more refined hydroelastic analysis of VLFSs by considering more realistic modeling of the constituents featuring in the analysis. The main contributions of these papers are used in the grouping of the papers under the following topics: wave forces, non-wave forces, VLFS models, VLFS shapes, mooring system, breakwaters, profiles of seabed, and anti-motion devices. The paper will also include a list of relevant conference proceedings, and websites containing valuable information on VLFSs.

2. Basic assumptions, equations and boundary conditions for VLFS analysis

The fluid–structure system and the coordinate system are shown in Fig. 2. The origin of the coordinate system is on the undisturbed free surface. The z-axis is pointing upwards, and the sea-bed is assumed to be flat at $z=-h$. The VLFS has a maximum length of $2a$ in the x-direction, a maximum width of $2b$ in the

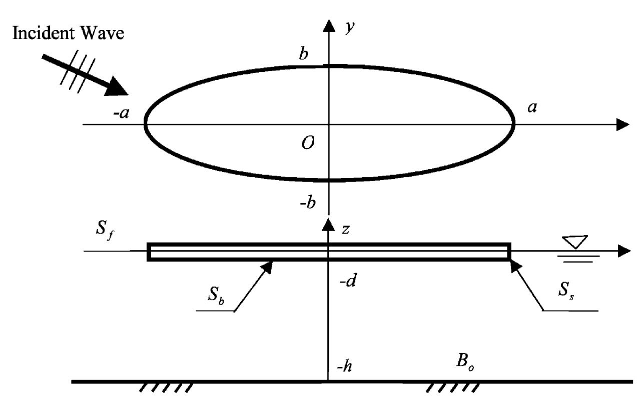

Fig. 2. Pontoon-type VLFS problem.

y-direction, and a draft d in the z-direction. The problem at hand is to determine the deflections and stress-resultants of the VLFS under the action of wave forces.

In a basic hydroelastic analysis of mat-like VLFSs, the following assumptions are usually made:

- The VLFS is modelled as an elastic (isotropic/orthotropic) thin plate with free edges.
- The fluid is incompressible, inviscid and its motion is irrotational so that a velocity potential exists.
- The amplitude of the incident wave and the motions of the VLFS are both small and only the vertical motion of the structure is considered.
- There are no gaps between the VLFS and the free fluid surface.

The analysis may be carried out in the frequency domain or in the time domain. Most hydroelastic analyses are carried out in the frequency-domain, being the simpler of the two. However, for transient responses and for nonlinear equations of motion due to the effects of a mooring system or nonlinear wave (as in a severe wave condition), it is necessary to perform the analysis in the time-domain. Below, we present the governing equations, boundary conditions and briefly described the commonly used methods for the analysis in the frequency-domain and in the time-domain.

2.1. Frequency-domain analysis

Considering time-harmonic motions with the complex time dependence $e^{i\sigma t}$ being applied to all first-order oscillatory quantities, where i represents the imaginary unit; σ, the angular frequency; and t, the time, the complex velocity potential $\phi(x,y,z)$ is governed by the Laplace's equation in the fluid domain,

$$\nabla^2\phi(x,y,z) = 0 \tag{1}$$

The velocity potential must satisfy the boundary conditions on the free surface, S_f, on the sea-bed, B_0, and on the wetted surfaces of the floating body, S_b (bottom surface) and S_S (side surface):

$$\frac{\partial\phi(x,y,z)}{\partial z} = \frac{\sigma^2}{g}\phi(x,y,z) \text{ on } S_f \tag{2}$$

$$\frac{\partial\phi(x,y,z)}{\partial z} = 0 \text{ on } B_0 \tag{3}$$

$$\frac{\partial\phi(x,y,-d)}{\partial n} = i\sigma w(x,y) \text{ on } S_b \tag{4}$$

$$\frac{\partial\phi(x,y,z)}{\partial n} = 0 \text{ on } S_S \tag{5}$$

where $w(x,y)$ is the vertical complex displacement of the plate, g the gravitational acceleration and n the unit normal vector pointing from the fluid domain into the body. The radiation condition for the scattering and radiation potential is also applied at infinity,

$$\lim_{r\to\infty}\sqrt{r}\left[\frac{\partial(\phi-\phi_I)}{\partial r} + ik(\phi-\phi_I)\right] = 0 \text{ on } S_\infty \tag{6}$$

where r is the radial coordinate measured from the centre of the VLFS, k the wave number, and ϕ_I the potential representing the undisturbed incident wave.

Assuming the VLFS as an elastic, isotropic, thin plate, the motion of the floating body is governed by the equation of a thin plate resting on a uniform elastic foundation:

$$D\nabla^4 w(x,y) - \sigma^2\gamma w(x,y) + \rho g w(x,y) = p(x,y) \tag{7}$$

where D is the plate rigidity, γ the mass per unit area of the plate, ρ the density of the fluid and $p(x,y)$ the dynamic pressure on the bottom surface of the plate. The pressure $p(x,y)$ is related to the velocity potential $\phi(x,y,z)$ by

$$p(x,y) = -i\rho\sigma\phi(x,y,-d). \tag{8}$$

The floating body, subjected to no constraint in the vertical direction along its edges, must satisfy the zero effective shear force and zero bending moment conditions for a free edge:

$$\frac{\partial^3 w(x,y)}{\partial n^3} + (2-v)\frac{\partial^3 w(x,y)}{\partial n\partial s^2} = 0 \tag{9}$$

$$\frac{\partial^2 w(x,y)}{\partial n^2} + v\frac{\partial^2 w(x,y)}{\partial s^2} = 0 \tag{10}$$

where n and s denote the normal and tangential directions and v is the Poisson ratio.

The commonly-used approaches for the analysis of VLFS in the frequency domain are the *modal expansion method* and the *direct method*. The *modal expansion method* consists of separating the hydrodynamic analysis and the dynamic response analysis of the plate. The deflection of the plate with free edges is decomposed into vibration modes that can be arbitrarily chosen. In this regard, researchers have adopted different modal functions such as products of free-free beam modes [6–13], B-spline functions [14], Green functions [15], two-dimensional polynomial functions [16] and finite element solutions of freely vibrating plates [17]. Also, it should be remarked that the modes may be that of the dry type or the wet type. While most analysts used the dry-mode approach [9,18] because of its simplicity and numerical efficiency, Hamamoto et al. [19–22] have conducted studies using the wet-mode approach. Next, the hydrodynamic radiation forces are evaluated for unit amplitude motions of each mode. The Galerkin's method, by which the governing equation of the plate is approximately satisfied, is then used to calculate the modal amplitudes, and the modal responses are summed up to obtain the total response.

In *the direct method*, the deflection of the VLFS is determined by directly solving the motion of equation without any help of eigenmodes. Mamidipudi and Webster [23] pioneered this direct method for a VLFS. In their solution procedure, the potentials of diffraction and radiation problems were established first, and the deflection of VLFS was determined by solving the combined hydroelastic equation via the finite difference scheme. Their method was modified by Yago and Endo [24] who applied the pressure distribution method and the equation of motion was solved using the finite element method.

Ohkusu and Namba [25] proposed a different type of direct method which does away with the commonly used two-step modal expansion approach. Their approach is based on the idea that the thin plate is part of the water surface but with different physical characteristics than those of the free surface of the water. The problem is considered as a boundary value problem in hydrodynamics rather than the determination of the elastic response of the body to hydrodynamic action. This approach was used to analyse a similar problem of two dimensional ice floe dynamics by Meylan and Squire [26]. Ohkusu and Namba [27] treated the VLFS as a plate of infinite length and velocity potential solved directly from a combined hydroelastic 6th-order differential equation. The deflections are estimated from the resultant velocity potential. The advantage of this method is that a closed form solution may be obtained in the case of shallow waters.

In Kashiwagi's direct method [28], the pressure distribution method was applied and the deflection was solved from the vibration equation of the structure. In order to achieve a high level of accuracy in a very short wavelength regime as well as short computational times and fewer unknowns, he uses bi-cubic B-spline functions to represent the unknown pressure and a Galerkin method to satisfy the body boundary conditions. His method for obtaining accurate results in the short wavelength regime is a significant improvement over the numerical techniques proposed by other researchers [6,17,18,29,30], who have also employed the pressure distribution method.

In sum, the principal difference between the modal superposition method and the direct method lies in the treatment of the radiation motion for determining the radiation pressure. For example, we observed that Takaki and Gu [17,18] used the shape function of dry eigen-modes of a plate with free edges while Yago and Endo [24] employed the shape function of a constant panel for the unknown pressure. The shortcoming of the constant panel method is that it is very difficult to deal with short incident waves that are important in VLFS analysis. In order to cater for the short wave case, Lin and Takaki [14] proposed the method be based on high-order B-spline panels.

2.2. Time-domain analysis

The commonly-used approaches for the time-domain analysis of VLFS are the direct time integration method [31,32] and the method that uses Fourier transform [33–37]. In the direct time integration method, the equations of motion are discretized for both the structure and the fluid domain. In the Fourier transform method, we first obtain the frequency domain solutions for the fluid domain and then Fourier transform the results for substitution into the differential equations for elastic motions. The equations are then solved directly in the time domain analysis by using the finite element method or other suitable computational methods.

3. Waves forces

Most papers on wave response analysis of VLFS assumed a linear wave. This assumption, however, is not valid when the wave steepness (product of wave number and wave amplitude) becomes large or when the water depth is very shallow in relation to the wavelength (as in the case of a Tsunami run-up originating from an earthquake). In order words, when the wave height becomes very large or when the water depth becomes very shallow, the nonlinearity of the wave becomes significant [38].

Wen and Shinozuka [39] and Wen [40] pioneered the study of floating plate strip subjected to nonlinear waves caused by high winds or by a Tsunami. Sakai et al. [41] carried out experimental and numerical studies on the hydroelastic behaviour of VLFS (modelled as a floating beam) under Tsunami. Masuda and Miyazaki [42] developed a method to estimate the Tsunami wave exciting forces for moderate size to very large floating structures. Ijima and Shiraishi [43] developed a response analysis method for VLFS located in coastal areas or inside reefs, for which it may be necessary to consider wave deformations due to the topographical effects, and these wave deformations can be nonlinear when the wave breaks. Based on the literature search, it appears that relatively little work has been done on the dynamic response of VLFS (modelled as a plate) when subjected to nonlinear waves.

Studies on hydroelastic behaviour of VLFS subjected to irregular waves have also been carried out. For instance, Miyajima et al. [44] investigated the elastic responses of Mega Float Phase II model under short crested irregular waves.

4. Drift forces and other forces

The evaluation of the wave drift forces is essential for designing mooring systems of a floating structure [45]. Conventional approach to calculate the drift forces may be based on the far-field method [46,47], where the distributions of radiated wave amplitude at very far-field from the floating structure are required. Kashiwagi [28] determined the drift force on VLFS by the far-field method, whereas Watanabe et al. [48] calculated the drift force on VLFS advancing with a small forward speed (or equivalently in a uniform current) based on the same approach and evaluated the wave drift damping. However, the far-field method can compute only the "total" wave drift force when the VLFS is close to breakwaters, or the varying depth of the seabottom near the VLFS is considered. Namba et al. [49] analysed drift forces by the near-field approach [50], but they ignored the draft effect which may not be neglected as the drift force dominates in the horizontal directions. Utsunomiya et al. [51] improved Namba et al.'s work to include the draft effect, as well as the horizontal motion of VLFS in the formulation of the drift forces. Namba et al. [52] carried out experiments to measure the drift force of a VLFS model and also performed numerical calculations to predict these drift forces. They presented a simple formula for evaluating the drift force that requires only a line integral of relative wave elevation around the platform.

As VLFS may be used as an airport terminal or airstrip, it is necessary to study its behaviour under the special impact and moving force due to the landing and taking off of an aircraft. Using an FEM program and the time-domain method, Watanabe and Utsunomiya [31] obtained numerical results of elastic responses due to impulsive loading on a circular VLFS. Kim and Webster [53] and Yueng and Kim [54] investigated transient phenomena on an infinite elastic runway. Watanabe et al. [32] studied the effect of airplane landing by using the time-domain method. Their computational model is very basic in the treatment of structure and/or fluid. Endo [36] made a more rigorous investigation of the transient behaviour of a VLFS under dynamic load induced by airplane landing and take-off. His study includes the following findings: (i) the airplane makes a V-shaped valley on the runway staying at its bottom and dragging it; (ii) in the wave condition, the magnitude of the vertical displacement of the runway is much greater than that induced by the plane; (iii) the airplane may experience a kind of surfing after it gains speed; (iv) the vertical motion of the plane induced by motion of the runway is very small even in the wave condition; and (v) the structural wave plays a significant role on adding the drag on the airplane, but the drag magnitude is very small. Kashiwagi and Higashimachi [55] conducted numerical simulations for transient responses of a floating airport due to landing and take-off by an airplane with realistic numerical data of a Boeing 747-400 jumbo jet. They showed that the airplane moves faster than the generated waves in the early stage of landing, and the waves overtake as the speed of airplane decreases when coming to a stop.

5. VLFS models

Some researchers [56–59] model the VLFS as floating beams. Such beam models may be suitable for ship but they do not reflect the two-dimensional action of a pontoon-type VLFS. Therefore, most researchers model the pontoon-type VLFS as a thin plate accordingly to the Kirchhoff's plate assumptions (see for example Refs. [10,28,60–62]). The plate is treated either as an isotropic or an orthotropic plate. The former assumption of an isotropic plate is used for a very rough analysis. For a more refined analysis that caters for the varying mass and stiffness that models for instance a floating runway, the VLFS is modelled as an orthotropic plate (see for example Refs. [17,18,23, 63–65]). In order to obtain accurate stress-resultants, the more refined first-order shear deformation plate theory proposed by Mindlin [66] has been used by many researchers [16,22,67,68]. The Mindlin plate theory allows for the effects of transverse shear deformation and rotary inertia which become significant in higher modes of vibration. Moreover, the Mindlin stress-resultants are defined by only first-order derivatives of deflection and rotations, as compared to their definitions in terms of second-order and third-order derivatives in the classical thin plate theory.

As VLFSs are usually constructed by connecting multiple standardized modules with connectors from the viewpoints of easy construction, transportation and deployment, VLFSs are sometimes modelled as module linked floating structure. Maeda et al. [69] studied the one-dimensional behaviour of floating structures consisting of rigid modules with rigid or pin connectors for regular waves by a strip method. Riggs and Ertekin [70] developed a three-dimensional hydroelastic analysis of module linked floating structures under regular waves with arbitrary angle by using FEM for structures and a strip method for the fluid. Takaki and Tango [71] investigated the wave drifting forces acting on a module linked floating structure which is joined by rigid or pin connectors by a three-dimensional panel method. Hamamoto and Fujita [19,20] developed a three-dimensional BE-FE hybrid analysis for module linked VLFSs. The floating structure is discretized by 8-node brick and 4-node quadrilateral finite elements, while the structure-water interface is discretized by constant linear boundary elements. Hamamoto [72] continued in this line of investigation by developing the hybrid BE-FE method with 8-node isoparametric elements and the Mindlin plate theory was used to allow for the effect of transverse shear deformation. The fluid–structure interface is discretised by boundary elements using 8-node parametric elements.

Xia et al. [73] modelled the VLFS as a two-dimensional articulated plate so as to capture the effect of welding joints as vertical and rotational springs connecting the adjacent modules with a variation of stiffness from zero (completely disconnected) to infinity (complete welding). They showed that the hydroelastic properties are strongly dependent on the stiffness of the connectors and the incoming wave frequency.

In trying to account for the complex internal structures of bulkhead type with attached deck and bottom platings, Fujikubo and Yao [74] investigated the modelling of the VLFS using the plane grillage model and the sandwich grillage model. They found that (i) the formula of torsional stiffness of the plane grillage model, based on the concept of equivalent strain energy, gives reasonable estimate of global elastic responses; (ii) the plane grillage model is not as accurate as the sandwich grillage model because of the neglect of Poisson's effect; and (iii) the sandwich grillage model must be used for more accurate prediction of stress responses.

6. VLFS shapes

A floating structure may take on any shape in practice. In the open literature, we have found that researchers have analysed pontoon-type VLFS of a rectangular planform (see for example Refs. [12,23,36, 75,76]). There are very few papers on non-rectangular VLFS, although the techniques developed could handle arbitrary shaped VLFS. Hamamoto and Fujita [22] treated L-shaped, T-shaped, C-shaped and X-shaped VLFSs. Circular pontoon-type VLFSs are considered by Hamamoto [60], Watanabe and Utsunomiya [31], Zilman and Miloh [77], Tsubogo [78], Peter et al. [79] and Watanabe et al. [80]. In a study report [81] published by the Japanese Society of Steel Construction in 1994, it was suggested that hexagonal shaped VLFSs be constructed as shown in Fig. 3 which allows for easy expansion of the floating structure. Hermans [82] discussed the treatment of a general geometric shaped VLFS. So it appears that more studies on VLFSs of non-rectangular shape should be carried out.

7. Mooring system

A mooring system is necessary to keep the VLFS in place. With a mooring system, the responses of a VLFS in waves do not include the hydroelastic vertical motions, but also the horizontal motions and the reaction forces of the mooring system. Research on the analysis of VLFS with the allowance for a mooring system was carried by Maeda et al. [83] and Shimada and Miyajima [84]. Takagi [17,18] studied the elastic deformation and mooring force of a VLFS on Tsunami waves using both theoretical simulations and experiments.

Consider a VLFS moored in a reef. When a high wave breaks at the reef face, tidal-bore shaped waves travel over the reef. These nonlinear wave pressures with short periods act on the VLFS and induce transient responses or ringing. The ringing can be, however, controlled by a mooring system consisting of a combination of dolphins and fenders. Studies on mooring system for VLFS moored in a reef have been conducted by Ookubo et al. [85] and Shiraishi et al. [86]. They

Fig. 3. Hexagonally shaped VLFSs.

carried out hydraulic model tests to determine the elastic response and mooring forces of a VLFS moored inside a coastal reef. They concluded that the response characteristics are significantly affected by the deformed nonlinear waves inside the reef and suggested further studies to be conducted to seek improvements in the design methodology for floating structures moored inside a reef.

8. Breakwaters

In order to reduce the wave amplitude impacting the VLFS, breakwaters are constructed nearby. Nagata et al. [11] developed an analytical method to determine the motion of an elastic mat-like VLFS in waves in a sea with a breakwater. They used the domain decomposition method to analyse the fluid region. Their results showed that the breakwaters effectively reduce the plate response for long waves but in the case of short waves, the reduction is not well-pronounced. Utsunomiya et al. [12] showed that the presence of the breakwaters surrounding the VLFS may be analysed using the higher order boundary element method (HOBEM) without any difficulty. Seto and Ochi [87] presented a numerical method for predicting the hydroelastic behaviour of VLFS in a complex water area shape that is sheltered by breakwaters and land. For the free-surface flow, they employed a hybrid finite/infinite element formulation to reduce the computational effort. Ohmatsu [88] developed an effective method for the hydroelastic analysis of VLFS, taking into consideration the mutual interaction effect between the VLFS and the breakwater where the partial reflection coefficient is included.

The above studies dealt with breakwaters that are gravity-type (or bottom mounted). Although such conventional breakwaters provide the best wave-breaking performance, they however cut off water flow around the VLFS and thus they cancel the ecological friendly merit. Moreover, the construction costs for bottom-mounted breakwaters may be high when the installation depth is deep. With a view to reducing costs, as well as to maintain the environmental friendly space, breakwaters which allow water to flow through openings at their bottom are proposed. Ohmatsu et al. [89] and Maeda et al. [90] considered various kinds of breakwaters such as the oscillating water column (OWC) type and structure embedded by OWC type breakwater. Takaki et al. [91] proposed a system consisting of a floating breakwater using submerged plate. Hong et al. [92] treated vertical barriers floating or fixed types and studied the hydroelastic responses of VLFS by varying the gap between the bottom of the breakwaters and the seabed. They concluded that the hydroelastic response of VLFS may be reduced by more than 70% by using single surface-piercing vertical wave barrier with 50% under water opening ratio and for double layer barriers, the additional effect is only expected when the same size barriers are deployed. The performance of multi-layered wave barriers is mainly governed by the barrier with the largest blockage ratio and additional submerged barriers have little effect.

9. Profiles of seabed

Most analysts assumed a flat seabed for their hydroelastic analyses of VLFSs. In reality, the seabed is not uniform in depth. For example, when the VLFSs are located near the coastline, the shallow water depth is usually varying with the shallow end near the beach/coastline. A changing water depth and seabed topography affect the wave parameters, such as wavelength, wave height, wave direction, wave reflection, wave deformation and radiation and scattering forces.

Takagi and Kohara [93] applied the ray-theory to handle the wave propagation changes due to water depth changes. The hydroelastic behaviour of VLFS is treated as wave propagation in the platform. The wave field around the platform and in the platform is represented as a summation of the wave rays. Their results obtained for the 5 km class floating platform with varying seabed topology show good agreement with the three-dimensional analysis results of Ohmatsu [94] and Iwahashi et al. [95]. However, it should be pointed out that the shortcoming of the ray theory is that the corners of VLFS are singular points. Takagi [96] solved the corner problem and it is found that the corner effect is inversely proportional to the square root of the distance from the corner. Therefore the corner effect is restricted to around the corners. Another shortcoming of the ray method is that the wave amplitude is suddenly changed along a ray that passes through a corner. Again, Takagi [97,98] showed that this shortcoming may be overcome by applying the parabolic approximation.

The consideration of a varying water depth and topography was also made by Utsunomiya and Watanabe [99] and Utsunomiya et al. [100] (see Fig. 4). Although the analysis of VLFS with a varying seabed topography is complicated by the large number of degrees of freedom, they are able to solve the problem rapidly by developing an accelerated boundary element method (based on the integral equation proposed by Teng and Eatock Taylor [101]) that utilises the fast multipole algorithm and the 8-noded quadratic element.

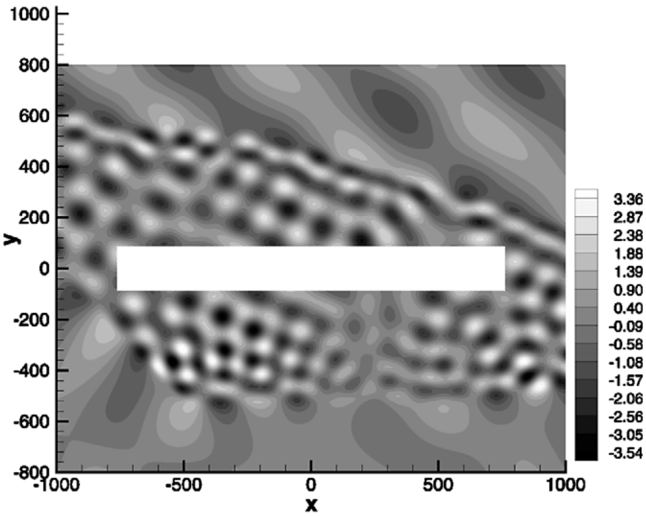

Fig. 4. Snapshot of water elevation around VLFS over variable water depth.

10. Anti-motion devices

When analysing the elastic motion of the Mega-Float, it was found that elastic motion appears as a propagation of water waves beneath a thin elastic-platform and its amplitude is not as small as previously perceived. Thus, researchers are prompted to develop an anti-motion device for VLFS. One such device is a box-shaped body attached to the edge of the VLFS. Takagi [97] and Takagi et al. [102] carried out numerical analysis, as well as experimental studies and showed that the anti-motion performance of this device is good at the design period, reducing both the deformation and the shearing force and bending moment of the platform.

Ohta et al. [103] carried out experiments to investigate the use of either a horizontal plate attached to the VLFS using vertical connectors (see Fig. 5) or a vertical plate attached at the edge of the VLFS in order to reduce displacements. They found that the horizontal plate is effective if it protrudes from one end of the VLFS and is placed at not too great a depth. For the case of the vertical plate attachment, they found that the effect of displacement reduction increases with increasing plate depth and decreasing wave period. They also concluded that a mooring system and these plate attachments would suffice in reducing motion without the need for breakwaters. Watanabe et al. [104,105] carried out wave response analysis of such VLFS with a submerged horizontal plate attached at the front end. Their analytical results based on the linear potential theory were in agreement with Ohta et al.'s experimental results, thereby verifying the use of the linear potential theory for analysing the response of a VLFS with a submerged plate.

Very recently, the Mega-Float engineers have used a flat vertical plate (with horizontal slits) which is attached to the edge of the IT base Mega-Float to reduce the drift. Other forms of plate attachments such as L-shape and reverse L-shape plates were studied by Ohta et al. [106]. These additional attachments reduce the hydroelastic response and mitigate horizontal motion and wave drifting force.

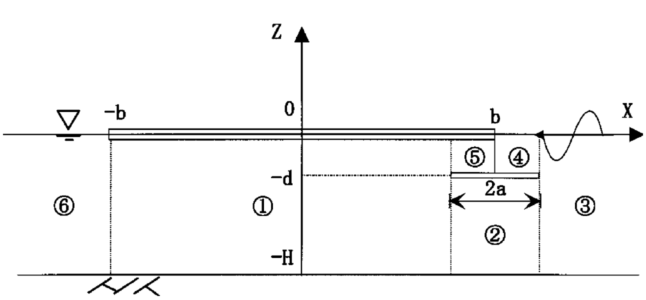

Fig. 5. A horizontal plate attached at the bottom of VLFS as an anti-motion device.

11. Future studies and directions on VLFS research

Despite much research being invested in the hydroelastic analysis of pontoon-type VLFS, there is still much work to be done. Future studies should consider

- *The effect of nonlinear waves*. Most analysis is based on linear waves which are not valid in extreme situations such as large storms. These extreme events have to considered in design for safety and survivability reasons.
- *Arbitrary shaped planforms for VLFS*. Most work so far dealt with VLFS of rectangular planforms, although the techniques available could handle arbitrarily shaped VLFSs. For more natural and aesthetically pleasing VLFS, the planform may take an irregular shape of a natural island. More analyses should be made on non-rectangular VLFSs.
- *VLFS with nonflat hulls*. So far, the hull of VLFSs has been assumed to be flat. There are few studies made on non-flat hulls.
- *Non-uniform seabed topography*. Most papers considered a VLFS on a uniform depth of water. More studies are needed to develop a fast method of analysis for handling the large computational effort in simulating the analysis where the seabed actual topography is used.
- *Developing simplified methods of analysis and models for design*. Current methods of analysis involve complicated mathematical models and techniques for solutions which are difficult to use for practising engineers. The results and experiences in developing these methods of analysis should be used to devise innovative simple models which capture the main characteristics of the problem and easy-to-use.

- *The use of smart anti-motion control devices.* So far the anti-motion devices are passive devices. Furukawa et al. [107] suggested the use of smart control devices to allow the motion of two floating modules of the Moby Dick (proposed floating Olympic Park at Osaka) to dissipate the energy so that the third module's motion may be negligible.

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Useful websites on VLFS

http://oceaneng.eng.hawaii.edu/~vlfs/
http://www.isope.org/
http://www.riam.kyushu-u.ac.jp/ship/
http://www.srjc.or.jp/megafloat/ (in Japanese)
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