Modular Multi-Purpose Floating Structures for Space Creation

Jian Dai, Øyvind Hellan, Arnstein Want and Kok Keng Ang

Abstract Modular multi-purpose floating structures (MMFS) are an innovative approach for space creation on the sea. The basic idea is to create "land on sea" by connecting a number of standardized modular units to form the desired size and shape for generic applications. The research presented in this paper was part of the multi-purpose floating structure (MPFS) project funded by the Land and Liveability National Innovation Challenge (L2 NIC) Directorate and JTC Corporation in Singapore. This paper presents an overview of the concept development and evaluation of the modular units and inter-modular connectors. Results from detailed structural and hydrodynamic analyses as well as scaled model tests show that the proposed solution is technically feasible. The construction methodology and preliminary cost estimate are also presented and discussed.

Keywords modular floating structures · connector · hydrodynamics · model test · construction

1 Introduction

Singapore is a condensed city-state. With a land space of only 710 km2, it is home to more than 5.8 million residents. In order to sustain the development growth, Singapore has been making efforts to create useable space for different purposes through various means such as high-rise buildings, land reclamation, underground

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utilization, etc. Among these approaches, the very large floating structure (VLFS) technology is also proposed as one viable way to create space on the sea. Construction of large floating structures is technically feasible in Singapore because of its benign sea state condition and strong offshore construction capability. Towards exploring and implementing large floating structure applications in Singapore, the Land and Liveability National Innovation Challenge (L2 NIC) Directorate and Jurong Town Corporation (JTC) funded the project Multi-Purpose Floating Structures (MPFS). The research work was carried out by the National University of Singapore (NUS), SINTEF and the Norwegian University of Science and Technology (NTNU) and included collaborative multidiscipline research including theoretical analyses, laboratory testing and evaluation of construction and maintenance costs. Besides the research institutions, Shimizu Corporation has also been invited to participate in this project to evaluate the engineering method for construction, installation and marine operations of the proposed floating structures, together with the cost estimation.

The MPFS project aims to develop innovative and optimal structural and foundation solutions, lightweight concrete recipes as well as construction methods for (1) hydrocarbon storage, (2) floating bridges and (3) modular multi-purpose floating structures. The research on the hydrocarbon storage focuses on the development of the world's first floating prestressed light-weight concrete storage facility with a capacity of 300,000 m3 [1,2]. The research on the floating bridge focuses on developing new design concepts for the ASEAN's first floating bridge spanning over 500 m of shallow waterbody [3,4]. An overview of the research activities on these two studies was given in [5].

The objective of the modular multi-purpose floating structures (MMFS) is to develop innovative solutions for the creation of "land on sea" of a desired shape and size for multiple applications. Some of the identified applications include floating aggregate storage facility, floating flatted factories, floating houses (dorms) and floating fish farms. Space creation is to be achieved by connecting a suitable number of modular floating units. These floating units and connectors should be standardized and optimized to reduce costs by ease mass production and optimized installation.

This paper presents the development of innovative design concepts for modular multi-purpose floating structures. Innovative concept designs and evaluation of the modular units and inter-modular connectors are presented. Results from structural and hydrodynamic analyses as well as scaled model tests are presented and discussed. In addition, this paper also presents the construction methodology and preliminary cost estimate of the proposed design concepts.

2 Design Concepts

As its name suggests, the design of modular multi-purpose floating structures should be generic with focuses on some specific applications. The specific applications are aggregate storage, flatted factories and housing properties. The concept should however be generic and not limited to these applications. Besides, the design shall meet a few requirements, including optimal basic shapes, sizes and connector designs, optimized use of sea space, fulfilment of classification rules and safety measures for floating structures, cost-effective solutions for logistics, construction and installation. The footprint of the deployment is 10 ha. The design working life shall be 60 years with minimum maintenance.

The design permanent and imposed loads vary with the application of the superstructures. It may be appropriate to categorize the design payload scale into three groups. In group 1, the average payload is smaller than 25 kPa representing greeneries, public space and 2-storey dorms/apartments. For group 2, the average payload ranges from 25 kPa to 45 kPa representing typical light industrial applications such as 2-storey flatted factories and low-rise housing properties such as 3-4 storied dorms/apartments. Group 3 is for heavy industrial applications with average payload beyond 45 kPa but limited to be less than 80 kPa. This limit is imposed in view of the loss of the advantage of the floating structure due to large draft to seawater depth ratios resulting in non-economical designs. Aggregate storage is one example of heavy industrial applications.

2.1 Shape and size of modular unit

The modular multi-purpose floating structures are formed by connecting several basic modules to form the required size and global shape. The research team has considered three options in basic shapes. Option 1 consists of rectangular modules connected in a staggered configuration with square and triangular modules at the edges and corners, as illustrated in Fig. 1. For convenience, this basic shape option shall be collectively termed “RECT”. Option 2 consists of only square modules, and thus termed “SQUARE”. Option 3 comprises hexagonal modules. It is termed “HEXA”. For all design options, the modular units are to be made of prestressed concrete with internal bulkheads serving as stiffeners.

From a preliminary comparison, design option 1 may provide wider choices in connecting modules, wider choices in inter-modular connection stiffness and natural straight edges for berthing purposes. The construction and fabrication are comparatively easier and cheaper. In addition, the regular shape enables easier planning of the superstructure. On the other hand, design option 3 provides a single standardized shape and size with corresponding optimal use of structural material and rigid inter-modular connection. Both design options also face their challenges. For example, there are three types of modular units needed in design option 1. Design option 3 lacks natural flat edges in the global layout for easy berthing unless half hexagonal modules are engaged. Design option 2 is considered in between in terms of the pros and cons.

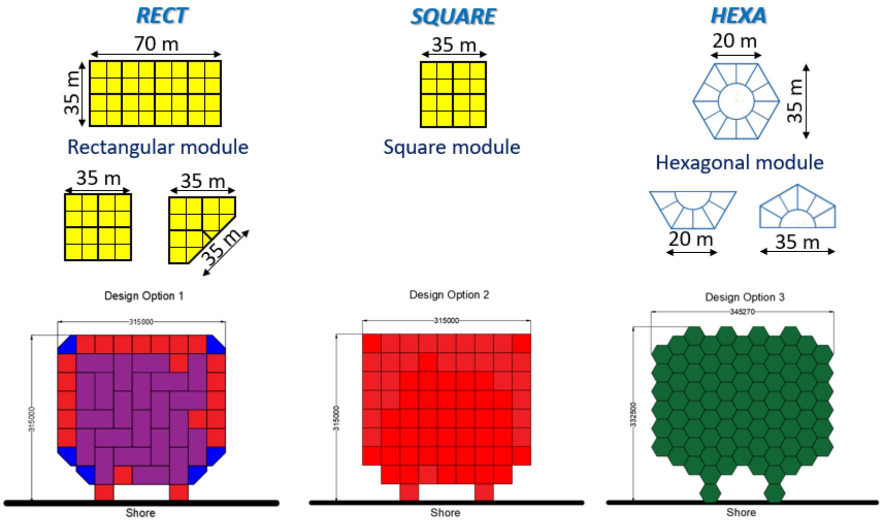


Fig. 1 Design options for modular units

2.2 Inter-modular connector

The design of the module to module connection is critical in the development of the MMFS. The connection should ideally have the capabilities such as self-alignment, impact attenuation, easy engagement and adequate strength [6]. Besides, it is desirable that to allow for a certain degree of rotational flexibility such that the moment developed due to environmental loads could be greatly reduced. For concrete floating modular units, the conventional design is based on the use of prestressing tendons/bars and shear keys. Figure 2(a) illustrates one example of connecting two concrete floating modules. The connection engages the modules through prestressed tendons both at the top and bottom of the modules. The tendons form a force couple that is capable of resisting moments developed at the connection interface. The shear to be transferred at the connection is taken by the shear key. Due to the prestressing of tendons, the connection is always engaged, thereby forming a rigid connection. Figure 2(b) gives another example by Hyundai based on prestressing bars that is used in the Incheon Concrete Floating Quay project [7].

It is essential to prevent the potential of water leakage and to ease the offshore activities by having the operation only at the top surface of the floating units. The research team brainstormed and proposed an innovative inter-modular connection, (see Fig. 3). This connector design comprises a top part with a tension member and a shear key. The top connector resists tension/splitting forces between connected modules and does not transfer moment. It can be used as a winch during the alignment of the modules. The shear key comprises a movable male part that can be adjusted up-and-down and in-and-out to cater for the construction tolerance. The up-and-down adjustment of the shear key is made possible through a jack. The in-and-out adjustment can be achieved by fitting in a shim plate. An alternative design with concrete shear keys is also proposed (see Fig. 4). Once the positioning of concrete shear keys is achieved, they can be grouted to the module using high-strength rapid-hardening grout.

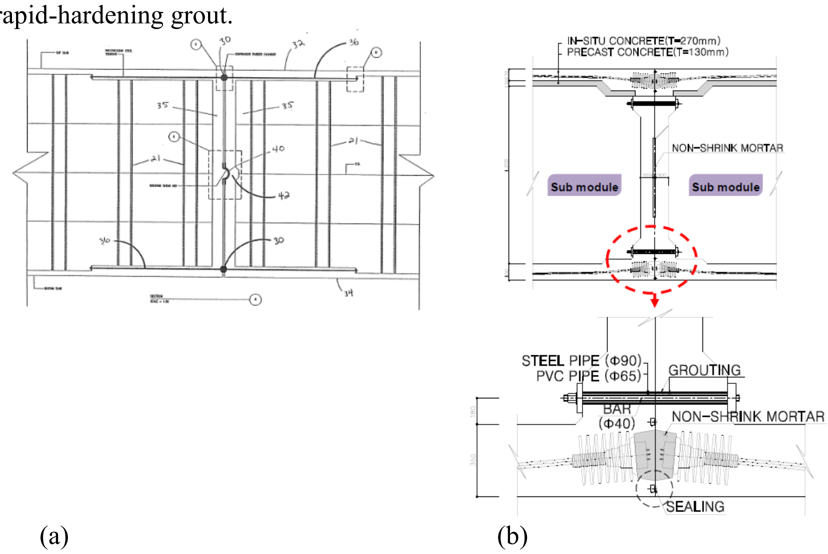


Fig. 2 Conventional connection designs: (a) design by Dr Alfred Yee and (b) design by Hyundai

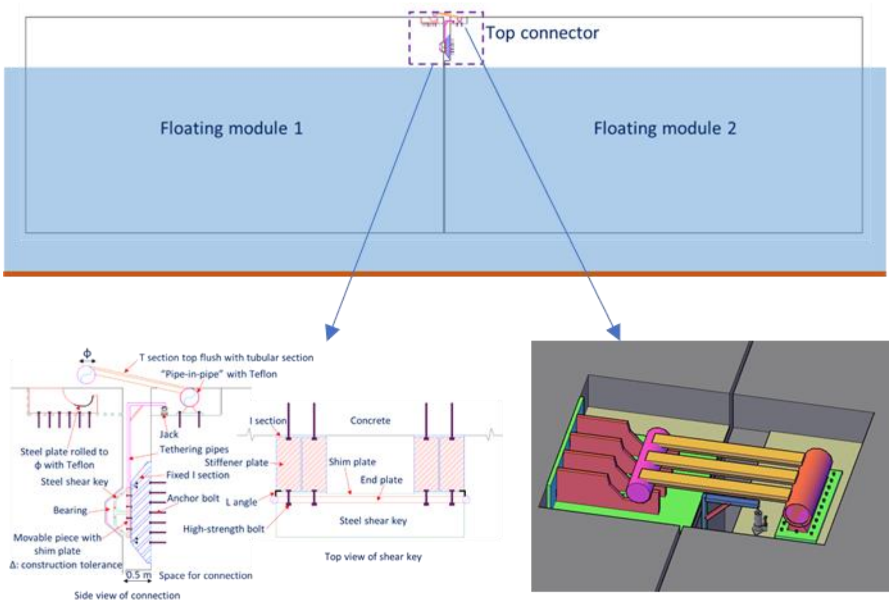


Fig. 3 New connection design for modular multi-purpose floating units with steel shear key

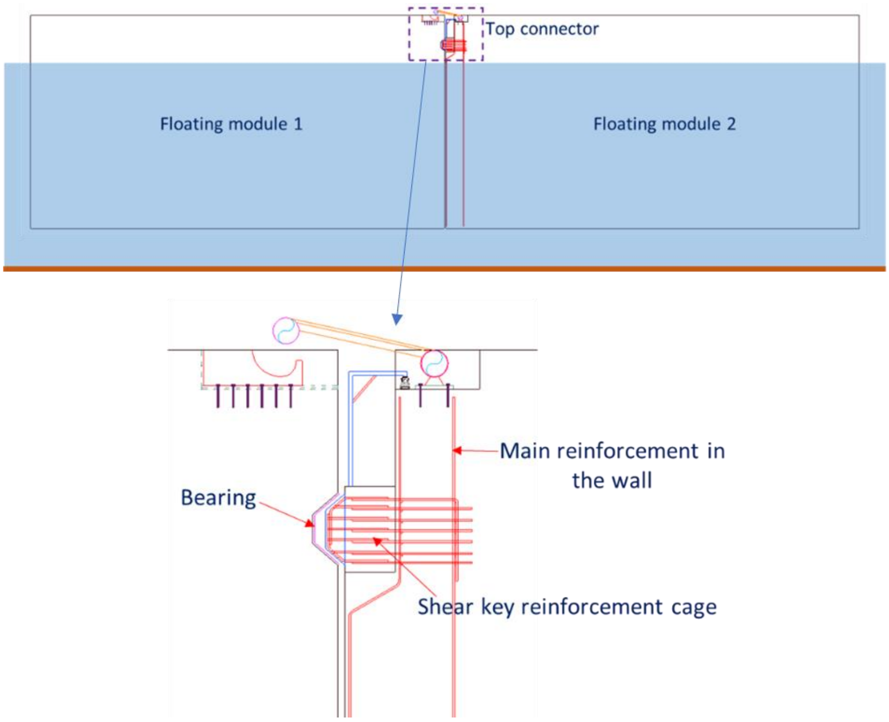


Fig. 4 Alternative connection design with concrete shear key

2.3 Station-keeping system

The development and evaluation of station-keeping solutions for floating structures involve several factors, including soil conditions, water depth, sea environments, sea-bed erosion and construction and maintenance costs. Based on the previous experiences on the hydrocarbon storage facility and floating bridges, it is concluded that mooring dolphin is a feasible foundation solution for floating structures in Singapore. This is in view that the soils could vary from layered soil to soft marine clay, the water depth nearshore is fairly shallow, and the sea conditions are relatively calm. It is also worth noting that the intended modular multi-purpose floating structure has a very similar overall geometry and thus environmental loads to the hydrocarbon storage facility. Thus, the mooring dolphin designed for the hydrocarbon storage facility is adapted here. An illustration of a mooring dolphin with inclined piles is shown in Fig. 5.

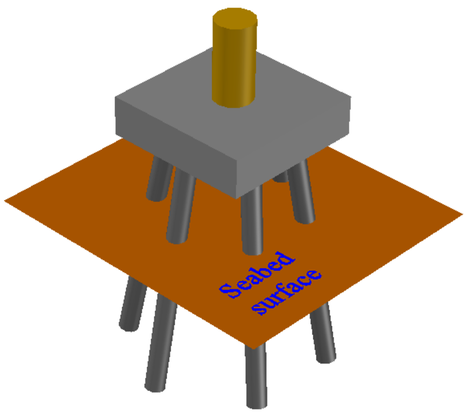


Fig. 5 Illustration of mooring dolphin

3 Concept Evaluation

Detailed evaluations are conducted to investigate the advantages and disadvantages of the proposed design options. These include the global analysis to evaluate the magnitude of forces developed at the connection, structural performance of modular units, hydrodynamic performance of truncated global layouts as well as buildability and construction economy.

3.1 Global analysis of connection force

The global performance of the three proposed design options is compared through detailed finite element simulations. A segment of the global layout of the MMFS is selected for the evaluation of the modules under various possible load patterns. Figure 6 shows the selected segments of the global layouts under four different loading patterns corresponding to the three design options. Finite element models are constructed accordingly based on plate theory with the properties idealized from the actual 3D modular model. Inter-modular connection stiffness is assumed to be rigid. The modules are supported by area springs to represent the hydrostatic pressure. Two different loading levels are considered, namely 25 kPa and 80 kPa, which represent the loading corresponding to a floating residential application and heavy-duty aggregate storage, respectively. This study aims to evaluate the shear forces and moments developed at the inter-modular connectors and how they are affected by the modular shape and size as well as the global configuration.

Different loading patterns are considered and the one inducing the highest connection loads for each design option is identified. This load pattern is then employed in a detailed study on the global connection loads. The total connection shear force, bending and twisting moments are obtained by scaling up the truncated numerical models to an equal global footprint. The results from the analyses are, listed in Table 1. The results show that the difference in shear force and twisting moment between RECT and HEXA is relatively small. However, the connection bending moment with HEXA is found to be 27% lower than RECT. SQUARE is also found to have the highest connection loads due to its long total connection length.

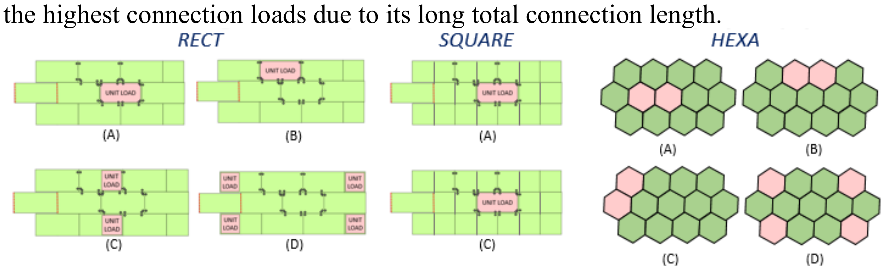


Fig. 6 Truncated global models and examples of possible load patterns

Table 1 Comparison of connection loads of different design options

Total connection load	RECT	SQUARE	HEXA
Connection length	805 m	1120 m	980 m
Shear (25 kPa)	432 MN	570 MN	450 MN
Shear (80 kPa)	1.3 GN	1.7 GN	1.3 GN
Bending (25 kPa)	11.5 GNm	14.4 GNm	8.4 GNm
Bending (80 kPa)	36.8 GNm	48.0 GNm	26.8 GNm
Twisting (25 kPa)	6.8 GNm	6.3 GNm	5.3 GNm

Twisting (80 kPa)	16.2 GNm	22.5 GNm	16.8 GNm

3.2 Structural performance of modular units

This section compares the structural performance of various modular units. In the comparative study, the highest loading level, i.e. 80 kPa representing heavy-duty aggregate storage, is considered. Finite element models are developed for the different shapes using the commercial software ABAQUS. Solid brick element (C3D20R) is used to discretize the main concrete structural components. The floating modules are supposed to remain in the linear elastic range of behavior at the service state. A linear elastic model is defined and the lightweight concrete density (including steel reinforcement) is assumed as 2000 kg/m3. The material input for the concrete model has a Young's Modulus, E, of 30 GPa and a Poisson's ratio, υ, of 0.17. Through iterative structural analysis using the finite element method with the consideration of a minimum freeboard of 2 m to ensure operational purposes, the total height of the floating modules is found to be 18.5 m. Note that such a heavy-duty application is meant for long-term strategic storage of aggregate. Therefore, frequent loading and unloading which may cause significant change in the draft of the floating modules are not expected.

Figure 7 shows the sectional view of a floating unit with considered loadings. The load of 80 kPa is applied as a uniformly distributed loading on the top slabs of the modular unit. The hydrostatic pressure due to seawater is taken into account. Springs are modelled beneath the base slab in the FE models to simulate the upward buoyancy effects. Draft values for each floating module are determined by balancing the upward buoyancy force with downward load effects.

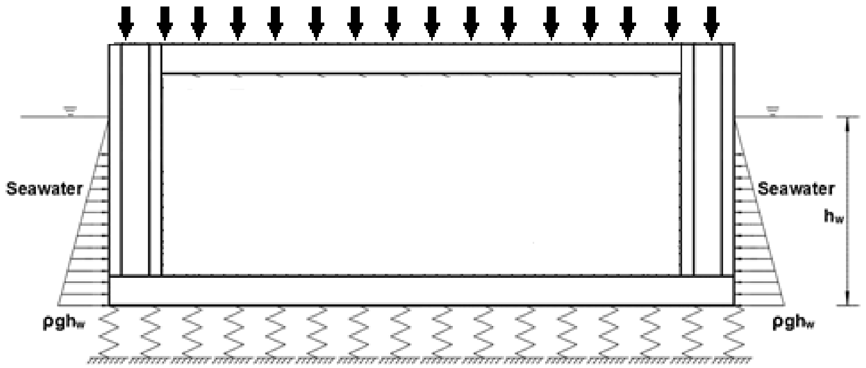


Fig. 7 Schematic diagram of loadings applied on arbitrary cross section

Table 2 summarizes the required amount of concrete and steel for the three different design options. More details regarding the finite element modelling and analysis results can be found in [8,9]. As it can be seen from Table 2, the three design options have similar structural performance. More specifically, RECT and HEXA have the same amount of concrete and steel, while SQUARE requires a slightly higher amount of the material.

Table 2 Concrete and steel usage for different design options

Design	Draft	Freeboard	Total concrete volume per planar area	Total steel weight per planar area
RECT	16.1 m	2.4 m	3.2 m3/m2	0.16
SQUARE	16.38 m	2.12 m	3.3 m3/m2	0.19
HEXA	16.5 m	2 m	3.2 m3/m2	0.16

3.3 Hydrodynamic performance of connected units

Both physical model tests and corresponding numerical simulations are carried out to evaluate the hydrodynamic performance of the proposed design options. In the numerical model, a one-line configuration made of connected square or hexagonal units is considered for the sake of simplicity, as illustrated in Fig. 8. In view of their geometric difference, 7 square modules and 8 hexagonal units are considered, respectively. Each modular unit is considered as a rigid body and the potential flow theory is applied to model the fluid. In each model, hinge connectors are used for the floating unit in connection to the quayside. Note that the model made of square units can also be used to represent the design option of "RECT" in view of the fact that each rectangular unit can be considered as two rigidly connected square units.

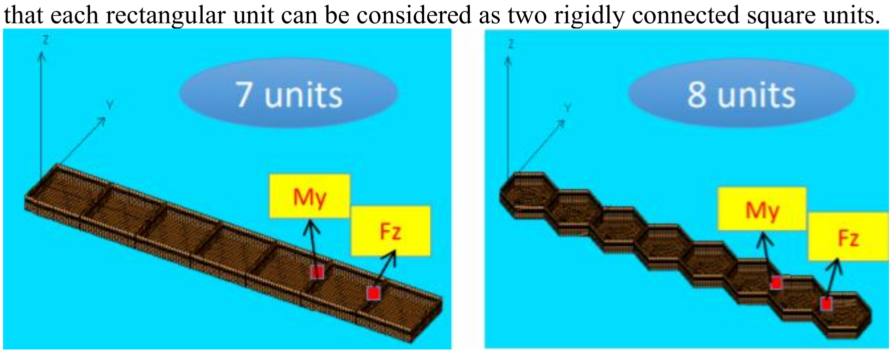


Fig. 8 Numerical models of connected modular units

Model tests of the proposed design concept were also carried out at the wave basin in the National University of Singapore during November 2018. The tests focused on the hydrodynamic behavior of the modular system in waves. Due to the limited area in the wave basin, it was not impossible to test an entire system.

Therefore, tests were performed only on systems comprising square units. Figure 9 shows the setup of an experimental model of 7 connected modular units at the wave basin.

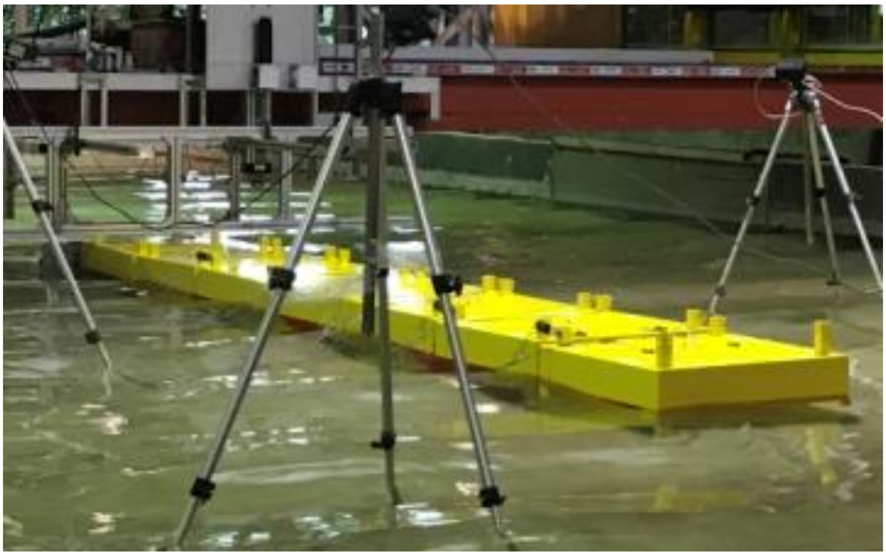
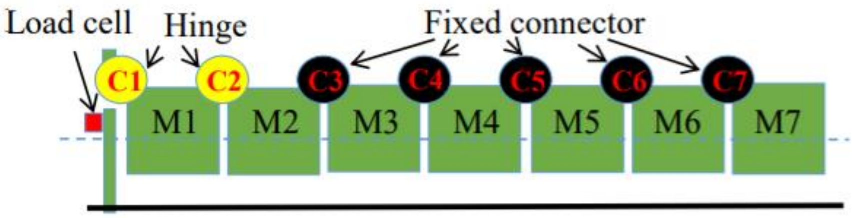


Fig. 9 Experimental model of one-line system

Figure 10 shows the comparison of the bending moment developed at the connectors from the numerical and experimental models. In the comparison study, regular waves with a wave height of 2 m and a period of 7 s in the longitudinal direction of the system are considered. Good agreement is found between results obtained by using the numerical model and experimental model. Although the numerical results tend to be slightly larger than the model test results. This slight overestimation is probably due to the uncertainty occurred during the experiment, such as the viscous effects or shallow-water effects. Nevertheless, the numerical model is verified and validated.



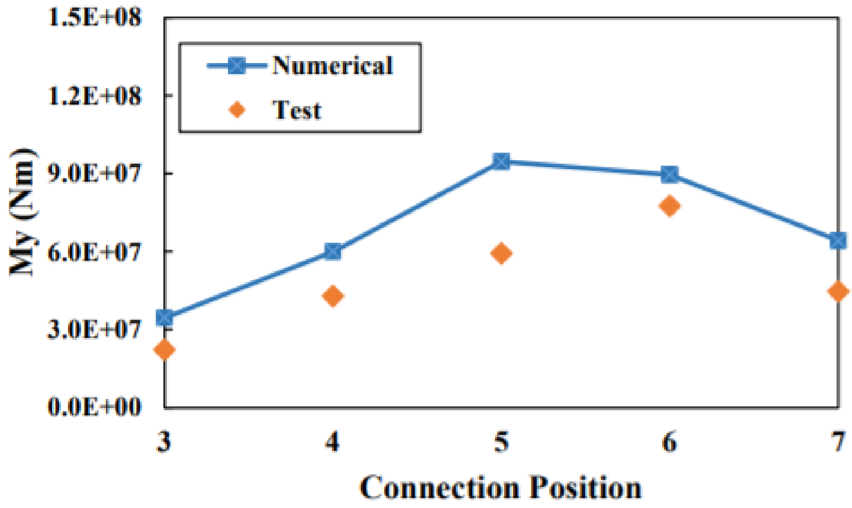


Fig. 10 Moment at inter-modular connections

The numerical model is next applied to investigate the difference in the hydrodynamic performance between square and hexagonal modular units. Table 3 lists the motion of floating units and connection forces developed under a 100-year sea state with a significant wave height of 1.8 m and peak period of 7 s. In general, the design option HEXA has slightly smaller motions and forces under wave actions. However, the difference between SQUARE, RECT and HEXA is rather small. For more detailed information of the hydrodynamic study, the reader may refer to [10,11]. It is worth highlighting that there was a large-scale model test conducted at SINTEF Ocean to examine the hydrodynamic performance of the proposed hydrocarbon storage facility [12]. The experimental results are also of important value in view of the fact that both applications have similar overall dimensions.

Table 3 Hydrodynamic performance of one-line modular systems

Parameter		SQUARE	HEXA	HEXA/SQUARE
Pitch (°)	Max	0.196	0.187	95.4%
	Min	-0.227	-0.212	93.4$
	Std	0.062	0.058	05.6%
Shear (kN)	Max	3.20E+03	2.90E+03	90.6%
	Min	-2.97E+03	-2.84E+03	95.6%
	Std	9.11E+02	8.40E+02	92.2%
Moment (kNm)	Max	1.34E+05	1.23E+05	91.8%
	Min	-1.30E+05	-1.20E+05	92.3%
	Std	3.82E+04	3.48E+04	91.1%

3.4 Buildability and cost comparison

Integration of superstructure and floating substructure may help to reduce the cost of a floating facility. Normally the design of floating structure starts with superstructure planning, and then design the floating structure corresponding to superstructure's size, height, column span. Following this process, it is possible to optimize the floating structure design and reduce the cost. However, since the current study focused only on the floating structure, the buildability and cost evaluation based on the schematic design are indicative only.

It is assumed that the footprint of superstructures covers 60% of the floating structure area with a plot ratio of 2.5, i.e. the ratio of gross floor area is 250%. The superstructure is 4-storied and a total payload of 40 kPa is assumed to be applied to the floating units.

For the construction of the modular units, it is recommended that they are fabricated using dry docks. There are only a few dry docks available in Singapore and the region which have the capacity of construction a few units concurrently. In general, all modular units can be constructed using standard methods. However, the hexagonal units have oblique sides which tend to introduce complications of the construction. An evaluation by Shimizu corporation shows that the buildability of HEXA design option is about 20% lower than RECT and SQUARE [13].

For the cost comparison, only indicative overall cost is examined. This is due to the fact that there are many uncertainties in the plan and details at the conceptual design stage. However, this indicative cost is aimed to be utilized as the basis for the purpose of further study of design and construction methods to reduce the cost. It should be noted that the estimation was conducted by Shimizu corporation using Japanese rates due to the lack of locally available information. The cost estimate includes concrete floating work and the landing/towing work. For the latter, the outfitting at quayside and offshore connection work as well as dock rental fee based on Japanese rates are considered. Also note that although the Japanese rates are used in the cost estimate, the study focuses on the relative cost between different design options. For the detailed analysis of the construction cost, other available fabrication facilities elsewhere may be consulted. However, this is outside the scope of the study.

The evaluation estimates that the total construction costs for RECT and SQUARE are virtually the same as they have a very similar geometry. HEXA has more modular units and the construction with oblique walls increases the cost for each module by about 20-30%. Overall speaking, the total construction cost for HEXA is about 15-20% higher than RECT and SQUARE [13].

3.5 Comparison of design options

With the studies on the global performance, structural behavior, hydrodynamic performance and buildability and cost-effectiveness, a quantitative comparison is made possible by assigning appropriate indices to the performance of the design options in each of the identified selection criteria with appropriate weightage, as shown in Table 4. Note that for all selection criteria, the performance of RECT is set to 1 and chosen to be the basis for comparison. Higher indices refer to better performance. In general, all design options are technically feasible. HEXA is found to perform the best in term of the global static performance owing to the natural interlocking mechanism with oblique connectors, followed by RECT and SQUARE in sequence. RECT scores the best in terms of ease of cost effectiveness, structural performance, construction, ease of marine operations and planning of super-structure. In view of this, it may be reasonable to choose RECT for further detailed research analysis and design.

Table 4 Comparison between design options

Selection criteria	RECT	SQUARE	HEXA	Weightage
Global static performance	1	0.78	1.37	40%
Hydrodynamic performance	1	1	1.07	10%
Payload carrying capacity	1	0.96	0.99	50%
Efficiency of structural system	1	0.89	1.15	100%
Buildability	1	1	0.8	-
Cost-effectiveness	1	0.95	0.87	-

4 Conclusions

This paper presents the development of innovative design concepts for a modular multi-purpose floating structure. Studies on the global static behavior, structural and hydrodynamic performance, station keeping system as well as buildability and cost economy are carried out. The results show that construction of large floating structures for generic applications in Singapore coastal waters is very doable because of the benign sea state and strong offshore industry capability. The study also reveals that all proposed design options are technically feasible. Considering both the efficiency of the structural system and cost economy, the design option comprising mainly rectangular modular units appears to have the best performance and thus can be chosen for future detailed research, analysis and design.

Acknowledgement

This research is supported in part by the Singapore Ministry of National Development and the National Research Foundation, Prime Minister's Office under the Land and Liveability National Innovation Challenge (L2 NIC) Research Programme (L2 NIC Award No L2 NICTDF1-2015-2). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not reflect the views of the Singapore Ministry of National Development and National Research Foundation, Prime Minister's Office, Singapore. The support from JTC Corporation is also deeply appreciated by the authors.

References

1. Dai J, Ang KK, Jin J et al (2019) Large floating structure with free-floating, self-stabilizing tanks for hydrocarbon storage. Energies 12:3487
2. Jiang D, Tan KH, Dai J et al (2018) Structural performance evaluation of innovative prestressed concrete floating fuel storage tanks. Struct Concrete 20:15-31
3. Wan L, Magee AR, Hellan Ø et al (2017) Initial design of a double curved floating bridge and global hydrodynamic responses under environmental conditions. In: Proceedings of the 36th International Conference on Ocean, Offshore & Arctic Engineering, Trondheim, Norway, June 2017
4. Wan L, Jiang D, Dai J (2020) Numerical modelling and dynamic response analysis of curved floating bridges with a small rise-span ratio. J Mar Sci Eng 8:467
5. Ang KK, Dai J, Hellan Ø et al (2020) Design and potential applications of floating structures in Singapore. In: Wang C, Lim S, Tay Z (eds) WCFS2019. Lecture Notes in Civil Engineering, vol 41. Springer, Singapore
6. Boldbaatar T, Yoon D-G (2013) A study on the connector of floating platform based on concrete structures. J Korean Soc Mar Environ Saf 19(1):37-44
7. Lee SH (2017) Modular floating structures. Workshop on Multi-Purpose Floating Structures, 1 March, Trondheim, Norway
8. NUS, SINTEF (2019) Modular multi-purpose floating structures: structural analysis and design of MMFS modules. Technical report no. 21 submitted to JTC
9. NUS, SINTEF (2019) Modular multi-purpose floating structures: structural analysis and design of MMFS connectors. Technical report no. 22 submitted to JTC
10. Ren N, Zhang C, Magee AR et al (2019) Hydrodynamic analysis of a modular multi-purpose floating structure system with different outermost connector types. Ocean Eng 176:158-168
11. NUS, SINTEF (2019) Hydrodynamic response of modular multi-purpose floating structures (MMFS). Technical report no. 20 submitted to JTC
12. SINTEF, NUS (2019) Floating fuel storage facility model tests. Technical report no. 29 submitted to JTC
13. Shimizu Corporation (2019) Construction methodology and cost estimate for MMFS. Technical report no. 28 submitted to JTC