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Tomoki Ikoma
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Chien Ming Wang *Editors*

Proceedings of the Third World Conference on Floating Solutions

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Preface

We are delighted to present this compilation of papers and research findings stemming from the 3rd World Conference on Floating Solutions, which was held in Tokyo from 28th to 29th August 2023. This international gathering convened an eclectic assembly of researchers, architects, urban planners, lawyers and designers specializing in floating structures, uniting minds from across the globe to explore and deliberate upon the dynamic realm of floating solutions across diverse domains.

In recent years, the notion of floating solutions has gained remarkable momentum, driven by the demanding challenges posed by climate change, coastal urbanization and the scarcity of resources. These formidable challenges have catalyzed creative thinking that quicken the development of a wide range of floating solutions that possess the transformative potential to revolutionize our interaction with the sea environment.

The primary objective of this conference was to furnish a platform for the exchange of knowledge, fostering profound connections and collaborative efforts in the endeavour to shape the future of global environmental solutions through floating structures. The conference's theme, "Floating Solutions for Next SDG's", resonated with the pressing issues and opportunities for change that confront the world today. The conference spanned a wide spectrum of subjects, encompassing, among other areas, floating architecture and urban planning, sustainable energy solutions on water, aquaculture and food production, disaster resilience, climate adaptation, regulatory policies for sustainable offshore developments and innovations in floating technologies.

The papers featured in this compendium embody the culmination of extensive research, experimentation and innovation within these domains. They showcase the remarkable strides made and underscore the potential of floating solutions to tackle some of the most formidable challenges we face.

In our capacity as the editors of this volume, we extend our heartfelt thanks to all the authors, reviewers and contributors who have generously invested their time and expertise, pivotal in transforming this conference into a resounding success.

We firmly believe that the knowledge and insights captured within these pages will serve as an invaluable resource for researchers, policymakers and practitioners, igniting a spark for further progress in the field of floating solutions.

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Developing a Sustainable and Smart Floating Structure Solution for Enhancing Liveability in Hong Kong's Crowded Built Environment

Xiao Lin Zhao, Jianguo Dai, Xiaoli Ding, Rutger de Graaf-van Dinther, Chien Ming Wang, and Brydon Wang

Abstract This paper presents a vision for a sustainable and smart floating structure solution (S2FS2) in Hong Kong. It highlights the key features of S2FS2, particularly the adoption of a hybrid approach combining both floating structure solutions and conventional land reclamation for the creation of habitable land from the sea. The paper discusses the challenges and opportunities in deploying a hybrid floating development. These include: examining sustainable and cost-effective construction strategies and materials for floating platforms and superstructures in view of the highly corrosive environment in Hong Kong; the optimal designs of multi-purpose floating platforms to carry a range of superstructures designed to meet various spatial programmatic and functional requirements and sites at different water depths; designing easy-to-instal, reliable, and durable connector systems for joining floating modules under the combination of dynamic (impact and fatigue) loading and a corrosive environment; rapid and precise on-site assembly of floating structures situated at different water levels using innovative construction technology and construction management; active control of dynamic structural movements in the sea during

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construction and service stages, particularly given the frequency of typhoons in Hong Kong; quantifying the ecological and environment impacts; and obtaining social acceptance. This paper also presents the estimated cost savings using a hybrid approach when compared to a conventional land reclamation approach based on the example of a proposed solution for the Kau Yi Chau artificial island (1000 ha).

Keywords Floating city · Hybrid solution · Cost comparison · Construction materials · Construction technology

1 Introduction

Embracing new economic opportunities, creating capacity for sustainable growth, and enhancing liveability are the three building blocks encapsulated in 'The Hong Kong 2030+: Towards a Planning Vision and Strategy Transcending 2030' [1]. To fulfil this vision, we must overcome the land shortage in Hong Kong, which is estimated to be approximately 3000 ha. Among the possible solutions suggested by the government, more than one third will be realised through land reclamation. Large-scale land reclamation has played, and will continue to play, an important role in creating land for urban development in densely populated coastal cities like Hong Kong. However, this solution also attracts criticisms relating to threats to the marine environment—particularly below the project footprint, the degradation of water quality, the disruption of current flow, the vast cost relating to the lengthy soil consolidation and construction periods, and the shortage of fill materials for land reclamation. Enhancing liveability requires a certain percentage of land (normally 20–30%) be used as recreational space and community facilities that are often not in the form of high-rise buildings. Floating structure solutions may complement land reclamation strategies by serving to provide space for such recreational and leisure functions on the adjacent water body. Figure 1 shows the water depth map of Hong Kong, where many regions have a water depth (above 5 m or 8 m) suitable for floating solutions.

This paper presents the vision for a sustainable and smart floating structure solution (S^2FS^2) in Hong Kong. It will cover the key features of S^2FS^2, highlighting its hybrid approach that combines the deployment of floating structure solutions with conventional land reclamation strategies for creating land from the sea. The challenges and opportunities of such a hybrid development will be discussed. These include sustainable and cost-effective materials for floating platforms and superstructures in view of the highly corrosive environment in Hong Kong; optimal designs of multi-purpose floating platforms to carry a range of superstructures designed to meet various spatial programmatic and functional requirements and sites at different water depths; designing easy-to-instal, reliable, and durable connector systems for joining floating modules under the combination of dynamic loading and a corrosive environment; rapid and precise on-site assembly of floating structures situated at different water levels using innovative construction technology and construction management;

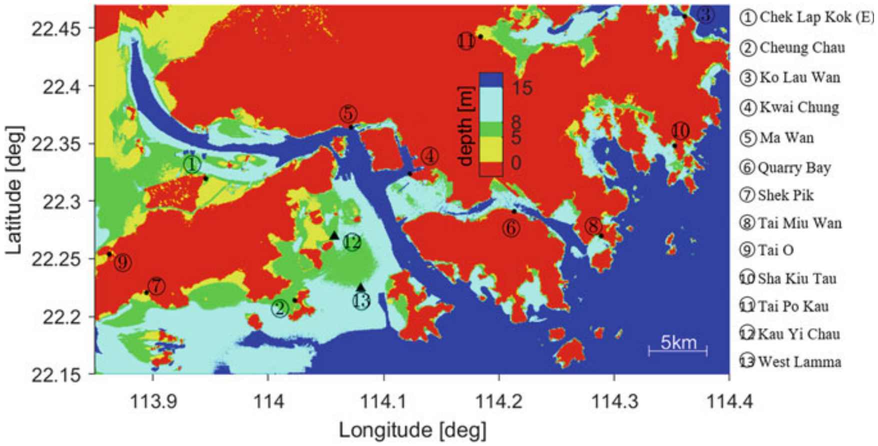

Fig. 1 Map of variations of water depths in Hong Kong waters (courtesy of Dr. Jinghua Wang). Regions of suitable water depth are coloured in cyan and blue above

active control of dynamic structural movements in the sea during construction and service stages, particularly given the frequency of typhoons in Hong Kong; quantifying the ecological and environment impacts; and obtaining social acceptance. This paper also presents the estimated cost savings using a hybrid approach when compared to the conventional land reclamation approach based on the example of a proposed solution for Kau Yi Chau artificial island (1000 ha).

2 Vision for a Sustainable and Smart Floating Structure Solution (S^2FS^2) in Hong Kong

The key features of sustainable and smart floating structure solution (S^2FS^2) are illustrated in Fig. 2, which consists of a floating platform on which superstructures are built with various functionalities for recreational spaces and community facilities. When compared with a traditional land reclamation approach, the advantages of using S^2FS^2 include: (i) a much shorter construction time as the mooring system, floating modules, and superstructure can be built simultaneously on different locations, and there is no need for a soil consolidation period; (ii) less environmental impact with minimal disruption to current flow, water quality degradation and impact on benthic life; (iii) flexibility in functionality and capacity to be reconfigured or relocated due to its modular and mobile nature; (iv) the structure not being affected by seismic action as floating structures are base isolated; and (v) being immune to the threat of flooding that may arise from a heavy downpour or rising sea levels.

This paper observes that from a policy perspective, the proposed S^2FS^2 could be more suitable than land reclamation in addressing future demands for land in

Fig. 2 Key features of S^2FS^2, a hybrid solution combining floating structures with land reclamation featured by low-rise recreational, public and green functions on floating platforms on the foreground, and high-rise buildings on reclaimed land on the background

Hong Kong and beyond as these artificial land parcels can be reconfigured to meet future changing needs, can be temporarily located at a particular site until they are more appropriately located elsewhere, and are not affected by a rising sea levels. We observe that S^2FS^2 provides a unique opportunity to meet the challenges identified below.

(i) The shortage of land for industrial estates in Hong Kong has been identified as a bottleneck in the re-industrialisation of the city (see *Guide to Hong Kong's Reindustrialisation*, HKPC 2020 [2]). Unlike conventional land reclamation where creating underground facilities would be costly and require extensive excavation and civil work, the unique nature of a floating structure solution allows the internal space of the floating pontoon base (i.e. the structure below the sea level) to be used for a range of functions. These include parking facilities, storage, and even industrial spaces, allowing industrial facilities to be co-located below recreational and cultural spaces.

(ii) The housing crisis in Hong Kong is one of the most pressing issues that the city is facing because the supply of public housing cannot keep up with demand. A hybrid floating solutions approach addresses this housing crisis in two ways: first, floating structures relieve demand pressures on Hong Kong's limited land. By re-locating leisure, recreational, and cultural functions onto floating structures, Hong Kong's limited land (including where expanded by conventional land reclamation) can be more efficiently applied to addressing public housing demands, allowing repurposing or optimising land use to maximise high-rise residential space. Second, floating structures can also be used to supplement housing stock on dry land. We suggest that low-to-medium density housing be provided and constructed on floating structures.

(iii) There is also a need for disaster (e.g. pandemic or earthquake) relief facilities. Housing facilities that are accompanied with sensitively designed communal areas could be used temporarily as quarantine facilities, flood shelter, and for emergency housing. Where a pressing need arises for the facilities to be used elsewhere, the floating structure can be unmoored, towed, and deployed to support any relief efforts.

(iv) The need for coastal developments to deal with rising sea level (note that approximately 90% of megacities worldwide are vulnerable to rising sea levels due to climate change with the disappearance of some islands in the Pacific Ocean in the coming decades [3]). Development of this hybrid solution will enable Hong Kong to be one of the early adopters of climate resilient buoyant urbanism and amphibious architecture through its development and use of floating structures.

3 Challenges for Developing S^2FS^2

Floating structures exist in various countries as shown in Fig. 3, e.g. the 1-km long Mega Float which is a floating runway test model built in Japan to study the feasibility of a floating airport; a performance stage at the Marina Bay in Singapore; a floating pavilion and a floating office building in Rotterdam; floating islands on Han River in Seoul; a floating beach in Oslo, Norway; floating theatre in Lyon; floating fire station in San Francisco; floating bridges in Washington State and in Norway; and floating residential houses in The Netherlands and Vancouver [4–7]. Additionally, there are plans to build a prototype floating city near Busan Metropolitan City [8] and a floating city in Maldives. All these floating structures are either built in calm waters or small in size for public access. Building large size floating structures to accommodate the needs in Hong Kong identified above is very challenging, especially pertaining to local oceanic, geographical, environmental, and climatic conditions and the types of land and space to be created. The various aspects of scientific and engineering challenges for developing S^2FS^2 are illustrated in Fig. 4.

3.1 Material Challenges

Developing emerging high-performance materials is of great importance to enable the structural and mooring systems integrity of S^2FS^2 to perform their functional, operational, and maintenance requirements over their design life spans. Floating pontoon-type platforms are subjected to severe mechanical and environmental loading actions during their service life (expected to be longer than 100 years), which require that

Fig. 3 Examples of existing floating structures **a** Mega Float, Japan (photo courtesy of Emeritus Prof. Eiichi Watanabe); **b** performance stage at the Marina Bay, Singapore; **c** Pavilion office building, Rotterdam; **d** floating islands on Han River, Seoul (photo courtesy of Y. S. Choo); **e** floating beach, Oslo (photo courtesy of Tor Ole Olsen); **f** floating theatre, Lyon <https://marineindustrynews.co.uk/calls-for-standardisation-of-floating-buildings/>; **g** floating bridges in Norway <https://www.aas-jakobsen.com/projects/nordhordlandsbrua/ > ; **h** floating residential houses in The Netherlands <https://www.weforum.org/agenda/2021/02/netherlands-floating-village-schoonschip-density/>; **i** prototype floating city, Busan [8]; **j** floating city, Maldives <https://worldarchitecture.org/article-links/enhfv/waterstudio-designs-world-s-first-true-floating-island-city-in-brain-coral-shape-in-maldives.html>

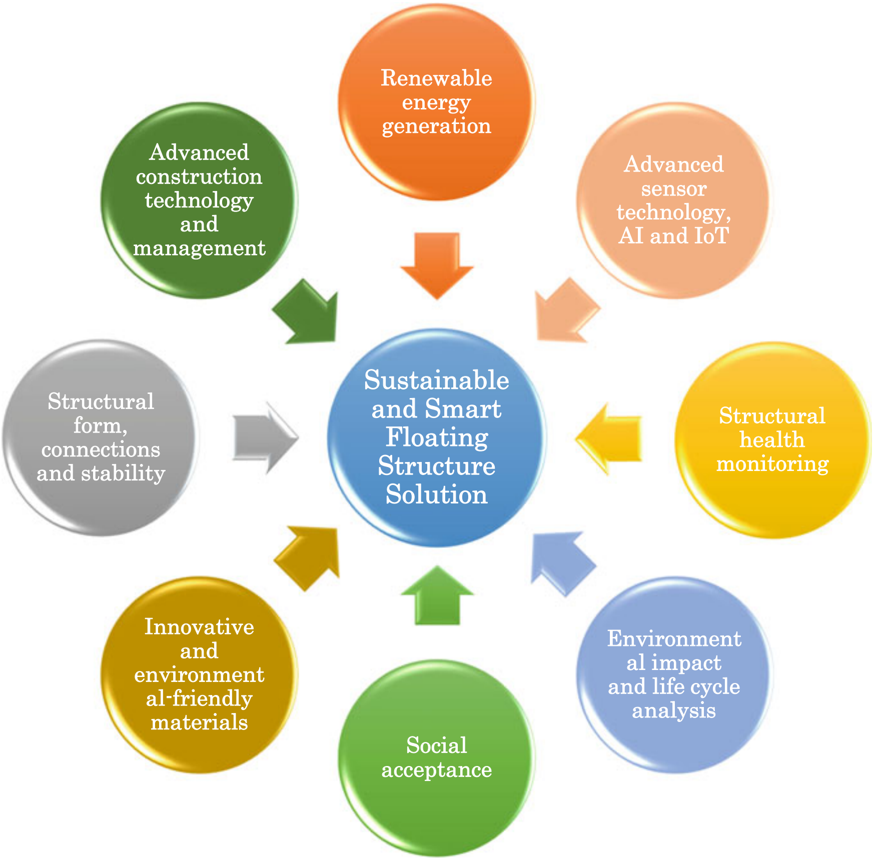

Fig. 4 Various aspects of scientific and engineering challenges for developing S^2FS^2

construction materials used in floating structures be strong, watertight, corrosion-resistant, and highly durable. On the other hand, the floating superstructures are preferred to be strong and light to accommodate more loadings against limited buoyancy. In case of shallow water, the floating pontoon could also be designed as a lightweight structure to facilitate improved buoyancy. Existing floating structures are constructed with either conventional pre-stressed concrete or steel, where the deterioration due to corrosion of steel reinforcement has been widely recognised as a hugely costly problem. The issue of steel corrosion prevention thus becomes very critical to minimise the maintenance needs. In addition, the hydrodynamic properties of the floating platform can be optimised by proper weight distribution achieved by a feasible combination of normal density and lightweight concrete of different qualities and unit weights [9]. Therefore, it is necessary to develop durable, lightweight, structurally efficient, low-carbon, and eco-friendly material solutions to support the S^2FS^2 in terms of both the pontoon platform and superstructure. Several types of materials will be developed and their performance extensively studied with respect to their possible service condition in S^2FS^2.

3.2 Structural Challenges

A suitable structural form needs to be developed for S^2FS^2 to meet the functional requirements with the consideration on the local oceanic conditions of Hong Kong. Large floating structure is a promising structural form to create large-scale environment-friendly and cost-effective place in the sea. Owing to the significant internal forces in the continuous large floating structure and the limitations in fabrication, transportation, and installation of large-scale floating platforms, modular construction (or called modular integrated construction, MiC) is optimal for large floating structures [10–12].

A modular floating structure for S^2FS^2 could consist of a low-carbon UHPC floating platform, MiC superstructures, connections, and mooring systems. Low-carbon UHPC will be reinforced by fibre-reinforced polymer (FRP) and pre-stressed by FRP-coated steel reinforcements to control crack development. The materials to be developed for the MiC superstructure will be lightweight low-carbon concrete core, with jacketing material (UHP-FRCC) to increase its durability. The proposed structural form would have the advantages of (i) short construction time; (ii) flexibility in functionality and relocation; (iii) high corrosion resistance to marine environment; and (iv) reliable performance under dynamic loads (e.g. impact and fatigue loading). Connections play an import role in the structural behaviour of modular floating structures [13, 14]. Connectors involved in an S^2FS^2 floating structure include the pontoon unit-to-unit, module-to-module, module-to-mooring system, and superstructure-to-platform connections.

The behaviour of the floating structure and its components needs to be well understood before a confident application. Unlike conventional fix-supported structures, the loads acting on a floating structure are dynamic and highly coupled, leading to a high complexity in analysing its structural behaviour. As the basic floating unit, behaviour of the novel low-carbon UHPC pontoon needs to be understood. Connectors are crucial to mitigate the displacements and accelerations in floating structures [15]. Effects of connector behaviour, such as rigidity, moment-rotation relationship, and damping behaviour, on the hydrodynamic response of the floating structure needs to be clarified. Owing to the interactive and coupling effects between water, wind, floating platform, superstructure, and mooring system, the overall behaviour of the floating structure is complex and requires much attention. In addition, effects of the corrosive environments and dynamic loads on the long-term behaviour of floating structures need to be investigated.

Design methods of floating structure will be different from that for conventional buildings and currently are scarce. There is a need to develop design methods and guidelines for large floating structures with proper consideration of the coupling effects between wave, wind and structures, and the corrosive environments.

3.3 Construction Challenges

The length of floating structures could exceeds 100 m [16] or even 1000 m [17]. Such a large size brings big challenges to the conventional construction method in buildability [18], transportation [19], installation [13], dismantling, reconfiguration, and reconstruction. Modular integrated construction (MiC) method could be more suitable for S^2FS^2, which will not only greatly reduce the requirements for yard construction capacity and very large floating dock [20], but also allow for a shorter project delivery time with the capacity for achieving a larger overall building size [5]. The floating modular pieces are towed to site and assembled on the sea. The floating modules and mooring system comprising the large floating structure design are generally fabricated within shorter timeframes and may even be fabricated through automated construction at various sites simultaneously under close supervision and controlled environmental conditions. This greater speed at which floating modules can be constructed, deployed, and assumed, when compared with conventional land reclamation processes, allows rapid monetisation of investment and offers potential savings in funding costs. There has been an existing examination of what is the appropriate module shapes, size (that has the strength, stability, buoyancy, easy for construction and towing), and connector system (that provides for ease of installation). Basic module shapes like triangle, square, rectangle, pentagon, and hexagon are certainly suitable. Czapiewska et al. [21] proposed the use of square and pentagon as basic shapes which can be used to create visually interesting floating platform shapes as shown in Fig. 5.

Ren et al. [13] at the National University of Singapore considered the various basic shapes and concluded that the square shape is the most economical one due to its ease in construction. Automated design tools have been deployed to aid in designing novel connectors that can reduce the effects of waves on floating installations. Ren et al. [13] found that the hydrodynamic responses of the modular multi-purpose floating system are sensitive to the effects of the connector types, the wave phase, and

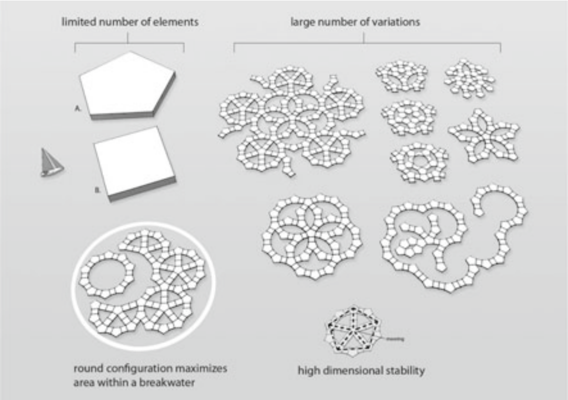

Fig. 5 Basic floating modular shapes for assembly to form interesting shapes [21]

the wavelength. The hinge-type design of the outermost connector can significantly reduce the extreme responses of stress resultants at the connectors. The additional PTO damper design for the outermost hinge-type connector can effectively reduce the motion of the outermost module and also produce considerable wave energy. With regard to the size of the module, Czapiewska et al. [21] observed that from a design perspective, 40–60 m platforms with a mean size of 50 m by 50 m will be a good size for construction and to ensure movability by tugboats. Larger wavelengths may present problems in terms of comfort. It is not structurally feasible to try and deal with this by making extremely large platforms. In order to solve comfort requirements, it is recommended that a more detailed study be done on how interconnected platforms with semi-flexible connections behave under different wave conditions. In the same vein, considering size, shape, type, and mooring, Adam et al. [22] also concluded that a square platform of 45 m by 45 m with height 4 m is the most appropriate modular platform design in view of stability, scalability, and ease of construction. However, careful construction control to safely connect segments on the sea is needed. In order to enhance the degree of construction precision for seaworks, it would involve performing 3D simulations using photo geometry data taken by drone before lifting, launching and joining the modules, as well as using latest laser scanning technology, UAVs, drone photogrammetry, and BIM models. There remains a clear need for further research to be conducted on standardised modular multi-purpose platforms for building floating infrastructure and hybrid floating cities economically.

3.4 Stability Challenges

Facing the complex ocean environmental loads, unknown seabed conditions, and strong nonlinear fluid-structure-soil interaction phenomena, a comprehensive understanding of this multi-physics fluid-structure-seabed coupling system is essential for structural design and regular operation to fulfil the serviceability and safety requirements of a marine floating structure. It is imperative to quantify the environmental loads including wind, waves, current, and water level. To gain insights of the coupling mechanisms, analytical approaches, numerical simulations, and laboratory tests on both the main floating platform and mooring system have been carried out for years [4, 23–30]. However, each of them suffers from its own drawbacks. For example, analytical methods are limited to simple geometries and explicit boundary conditions; numerical methods suffer from obtaining accurate models; and laboratory tests are often challenged by the small scale and simplicity. The fast developed structural health monitoring (SHM) strategy is a promising solution to measure the real external loads and structural performance in real time through different types of sensors. However, the number of sensors is always limited and cannot cover all components of a large-scale floating structure and mooring. Conducting the condition diagnosis and prognosis of floating structures using the data from sparse sensors are difficult and challenging. There is a need to develop a holistic platform by integrating laboratory experiments, numerical simulations, and SHM to study the multi-physics fluid-structure-seabed coupling system.

When large floating structures are deployed in very energetic or exposed offshore sites, it is necessary to construct breakwaters to attenuate the wave forces impacting on the floating assets. There are bottom-founded breakwaters as well as floating breakwaters. The latter type of breakwaters is preferred for sea sites with soft seabed and deep waters since they do not require a huge amount of fill materials and a long construction time for seabed foundations like the traditional bottom-founded ones. When compared to bottom-founded breakwaters, floating breakwaters also possess the following advantages:

- they allow for water circulation through the gap between the seabed and the lower hull of the breakwater, which can result in improving water quality and minimising impacts on marine ecosystems in the lee side of the breakwater;
- they have a low profile relative to the water surface for all tidal periods, which minimises their presence on the horizon;
- they can be rearranged, removed, relocated, expanded, and downsized more easily.

More recent designs of floating breakwaters allow multiple uses for the floating breakwaters. For example, the Monaco floating breakwater interior space is used for car parks and shopping mall as shown in Fig. 6. In the proposed floating forest by Wang et al. [31], the floating breakwater mooring head may be mounted with wind turbines for power supply and its deck carries windbreaks for protecting the floating asset from strong winds. Another recent floating breakwater design is to have porous breakwaters porous that allow free passage of water through its water channels to dissipate wave energy more efficiently and help in reducing the mooring forces [32]. More information on recent research and developments of floating breakwaters may be obtained from the review paper by Dai et al. [33].

Fig. 6 Monaco's floating breakwater <https://www.fdngroup.nl/floating-breakwater-in-monaco>

3.5 *Sustainability Challenges*

There is a lack of research in quantifying the environmental impact of floating structures on aquatic systems or various benefits and opportunities for ecology development. We need to study whether S^2FS^2 related pollutions, including hazardous substances, inorganic and organic nutrients, artificial light, and noise may disturb marine fishes and mammal. The water quality and ecological impacts should be monitored during the construction and operation of a S^2FS^2 structure. It is worth investigating the positive environmental aspects of the floating structure by testing its potential as green aquaculture infrastructure.

To support ocean floating communities, advanced hybrid ocean renewable energy systems should be considered to improve energy matching capability and the technical-economic-environmental performances of the overall floating system. Although some studies were carried out on life cycle assessment of offshore wind turbines [34], very limited work was found on LCA of floating cities. It is worth studying the environmental impact of the floating structure through building information modelling (BIM)-enabled life cycle analysis (LCA).

The potential of floating structures to provide climate resilient living space has recently been acknowledged by the United Nations and the IPCC. To address global climate challenges at the appropriate scale, upscaling of floating structures requires the development of multifunctional floating urban concepts and port concepts which can be realised on these structures. To this end, an understanding is required of the social, economic, and legal barriers and opportunities related to living on the water and building floating communities. Key governance challenges include the societal acceptance of large-scale floating concepts, and the development of enabling legal frameworks and governance arrangements that contribute to economically viable solutions through sustainable business models.

4 Estimated Cost Savings

A preliminary cost of land reclamation (100% land reclamation) versus a hybrid solution (75% land reclamation, 25% floating) combining land reclamation and floating structures was prepared for the Kau Yi Chau artificial island (1000 ha) case study. Table 1 presents the assumptions and data sources used for the comparison. In the hybrid case, 75% of the plan area will be created with land reclamation and 25% (non-high-rise functions) will be realised with floating structures. These floating structures are realised in relatively protected water which is created by the land reclamation part of the development. In the land reclamation case, the total plan area will be created with land reclamation. Table 1 gives the cost items that were used for the comparison. The following assumptions were made:

- The cost items for floating functions above include the mooring system and module connectors.

Table 1 Monaco's cost items and data sources that were used in the comparison study

Cost item	Value	Data sources
Typical cost of land reclamation	HK$ 16,500/m^2	(1), (2), (3)
Typical costs of a low-rise (< 4 floors) floating building in protected waters	HK$ 14,500/m^2	• Low-rise buildings, 3 floors, offshore (4); • Low-rise area, 4 floors, offshore (5) and • Low-rise area, 3 floors, tidal, protected water (6)
Typical costs public space	HK$ 3500/m^2	(7)
Typical costs light floating roads	HK$ 3500/m^2	
Typical costs sports and recreation space	HK$ 4250/m^2	

Data sources

(1) IPSOS Report (2018) Industry overview, https://www.hkexnews.hk/listedco/listconews/sehk/2018/1030/a17419/efullwealth-20181011-13.pdf
(2) https://hongkongfp.com/2019/03/19/hong-kongs-lantau-development-projects-cost-least-hk624bn-says-govt/
(3) CEDD (2022) https://www.cedd.gov.hk/filemanager/eng/content_83/indices%20Aug%202022.pdf
(4) Seasteading Institute (2014). Seasteading Implementation Plan. https://seasteadingorg.wpenginepowered.com/wp-content/uploads/2015/12/DeltaSync-Final-Concept-Report.pdf
(5) Roeffen, B, Czapiewska, K.M., Lin, FY (2020) Business Case Living@Sea D1.3. Report published in Space@Sea project for European Commission. Grant Agreement No. 774253 https://www.blue21.nl/wp-content/uploads/2021/01/d1.3.pdf
(6) Blue21 (2022) Internal construction costs database, industry information
(7) Blue21 (2022) Internal construction costs database, industry information

- Construction costs in Europe and Hong Kong are assumed to be similar. In reality, the labour costs are much lower, building materials are about the same price, and land (not relevant in case of floating developments) is much more expensive in Hong Kong.
- Additionally, it should be mentioned that floating structures can be produced elsewhere in the region, or even in other countries, where the construction costs are much lower. The floating structures can subsequently be transported to Hong Kong.
- HK$ to EUR to conversion ratio is 0.122.

Table 2 presents the results of the preliminary comparison. The results show that 16.5% of costs savings could be achieved. For a total development of a 1000 ha, this would add up to a total potential savings of 27 billion HK$.

Since conservative assumptions were made, the cost comparison is on the conservative side and even more favourable results might be achieved. This needs to be investigated more precisely in follow up research.