Delta Marine Consultants

Our Future Coast –
Flexible & Hybrid Protection for Climate Change Adaptation

Speaker: Bas Reedijk
Delta Marine Consultants

(Key Team Member: Chim Yan Qi, Jayce Tang Chai Hwa, Michiel Muilwijk, Tim Ruwiel, Yang Zi Qian)

Background

- Coastline threatened by flood and storm hazard
  - increased vulnerability due to climate change uncertainty with sea level rise and intensified storm
- Small island state like Singapore face challenges in adaptation:
  - limited physical size → no / limited retreat
  - high intensified land use
  - high population density and low social risk appetite
  - limited natural resource
- Crucial to develop resilient and sustainable coastal protection and adaptation strategy
- Singapore’s varied coastline requires diverse approaches towards climate resilience – our innovation meets the adaptation need

(area vulnerable to sea level rise in Singapore, *source: PUB*)

Hybrid Protection –

Combine Flexible Measure with Nature Based Solution

(Chim Yan Qi, Bas Reedijk, Michiel Muilwijk, Tim Ruwiel, Yang Zi Qian)

Delta Marine Consultants

Background

Delta Marine Consultants

- Growing interests in building with nature and integration of nature-based feature (green) with coastal structure (grey)
- Previous studies generally focus on larger-scale mangrove protective capability and engineered structure more to serve for mangrove rehabilitation temporarily
- We have constructed physical model test in our Netherland wave flume to investigate the performance of hybrid protection system integrating mangrove and hardened structure for coastal protection:
    - combined effect of mangrove and hard structure in wave attenuation (compare with each system acting alone)
    - contributing effect of mangrove fringes with modest thickness
    - characterization of wave-vegetation-structure interaction
- We consider hybrid protection system application in Singapore as starting point – moderate wave & surge height, short-period wave, the design can translate for implementation at similar coastal condition:

where nature eco-system alone is not adequate to stop inundation, integration with hard engineering solution is desired

Rhizophora mangrove as study focus

(amour build up placing mangrove at right elevation MSL - MHWS)

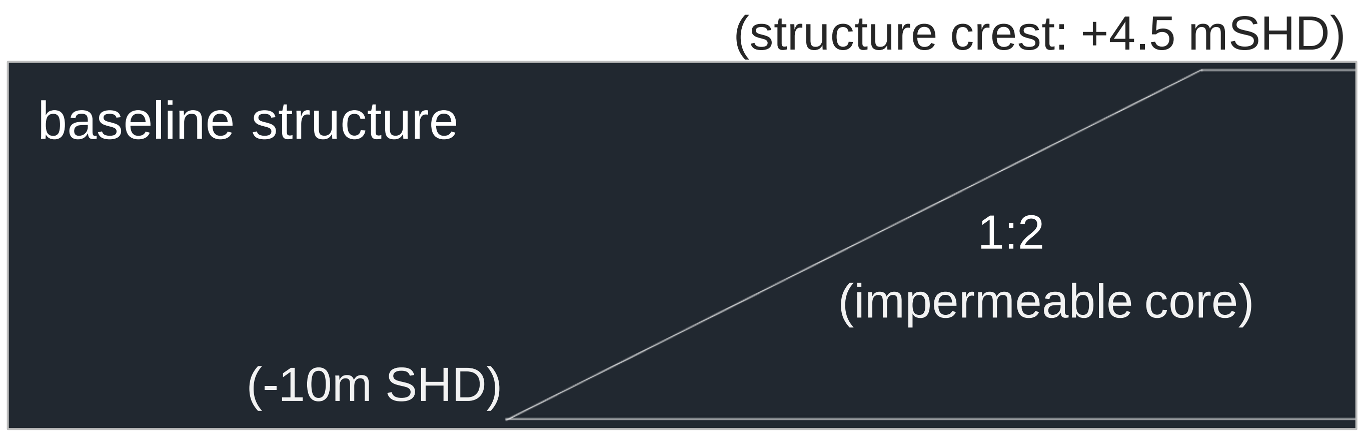
Xbloc+ armour as grey structure

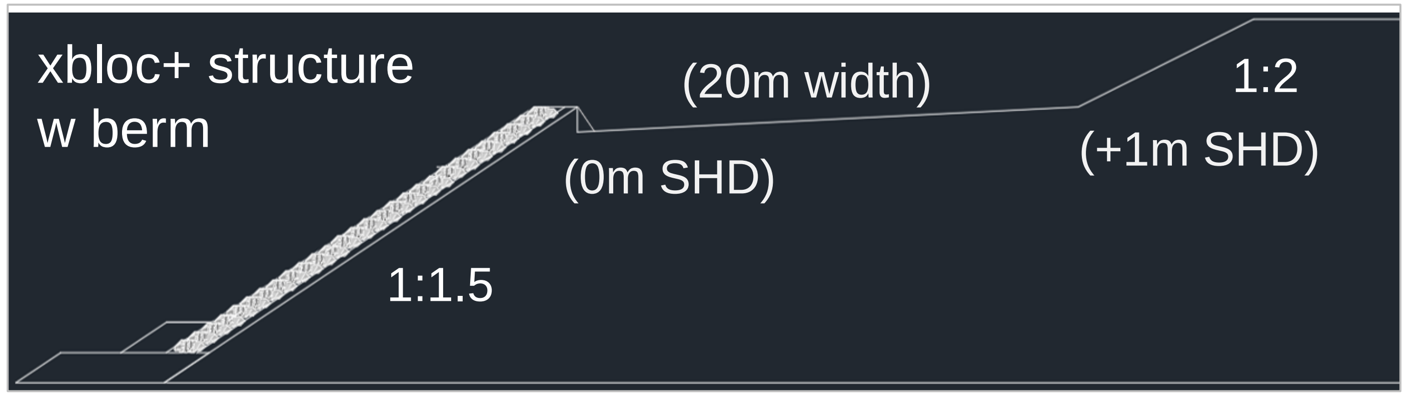
(low-crested armour on seaward slope reduce wave energy)

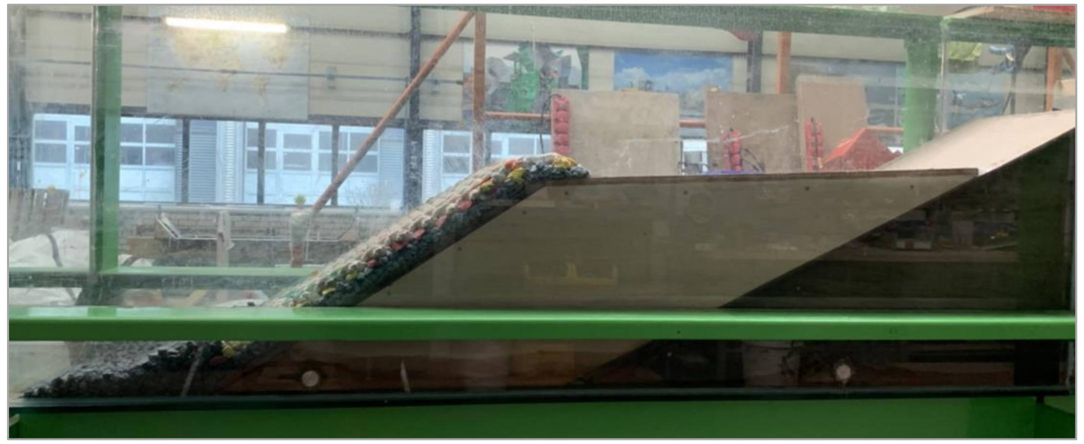
(establishment of moderate mangrove thickness on extended or new coastline)

Physical Model Experiment

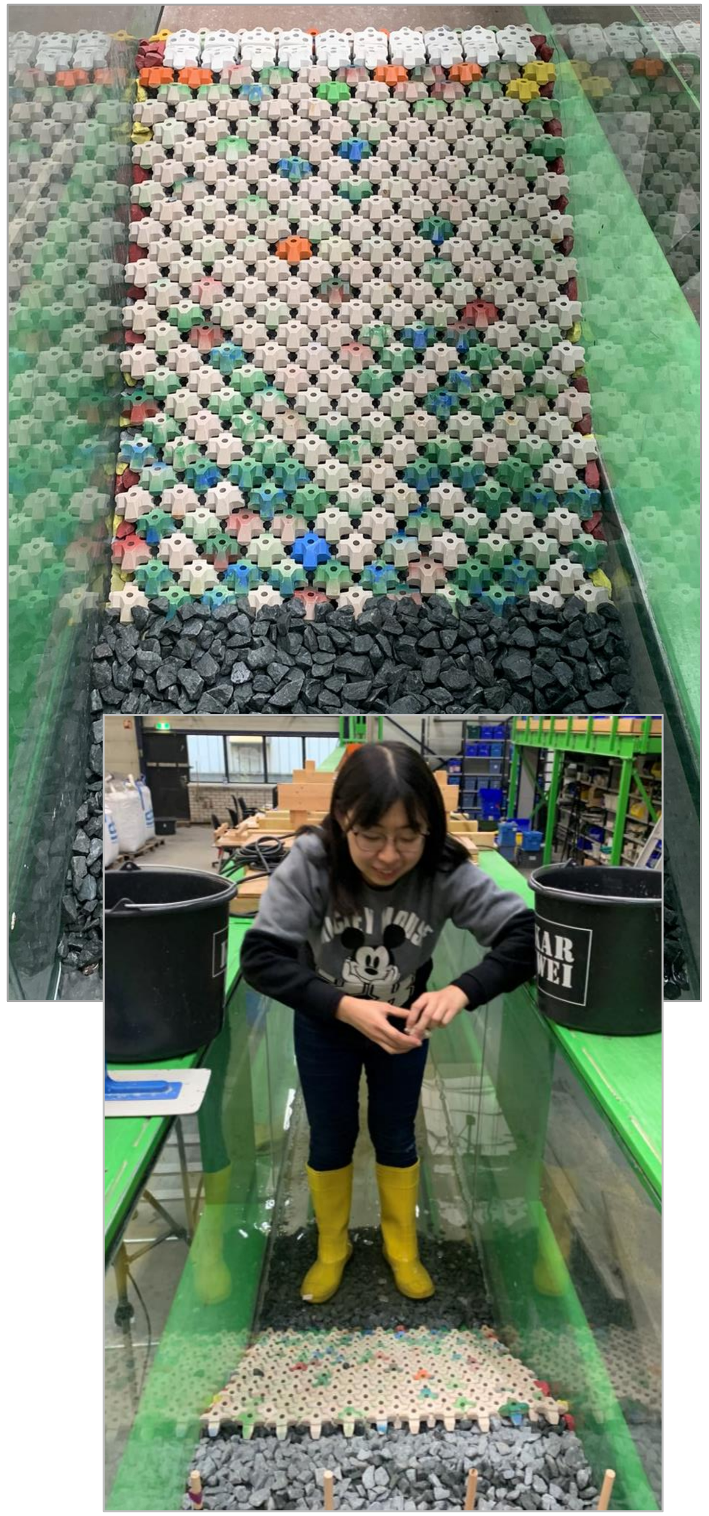
Delta Marine Consultants







(Xbloc+ armour)



(SHD refers to Singapore Height Datum, where 0m SHD = MSL)

optimize original Xbloc+ for moderate wave climate like Singapore coast

Test Condition

- Mangrove prototype parameterization:

  - trunk diameter at breast height 0.2m
  - highest root height 2m
  - number of primary root 22
  - mean root diameter 0.04m
  - largest root-spread distance from trunk 1.5m

  (referenced to Ohira et al., 2013)

  - mangrove spacing 3m, in staggered configuration
  - mangrove density 9.7 trees/ 100m2 (prototype scale)

- Test program (model length scale: 19.8)
  - three water levels

prototype	model
2.1 m SHD	0.611 m
2.5 m SHD	0.631 m
2.8 m SHD	0.647 m

(water depth from seabed)

  - four wave conditions (1000 waves tested for each run)

prototype		model	
wave height (Hs)	wave period (Tp)	wave height (Hs)	wave period (Tp)
1.5 m	4.9 s	0.076 m	1.10 s
1.8 m	5.4 s	0.091 m	1.21 s
2.1 m	5.8 s	0.106 m	1.30 s
2.4 m	6.2 s	0.121 m	1.39 s

(potential implementation at new coastline of East Coast reclamation)

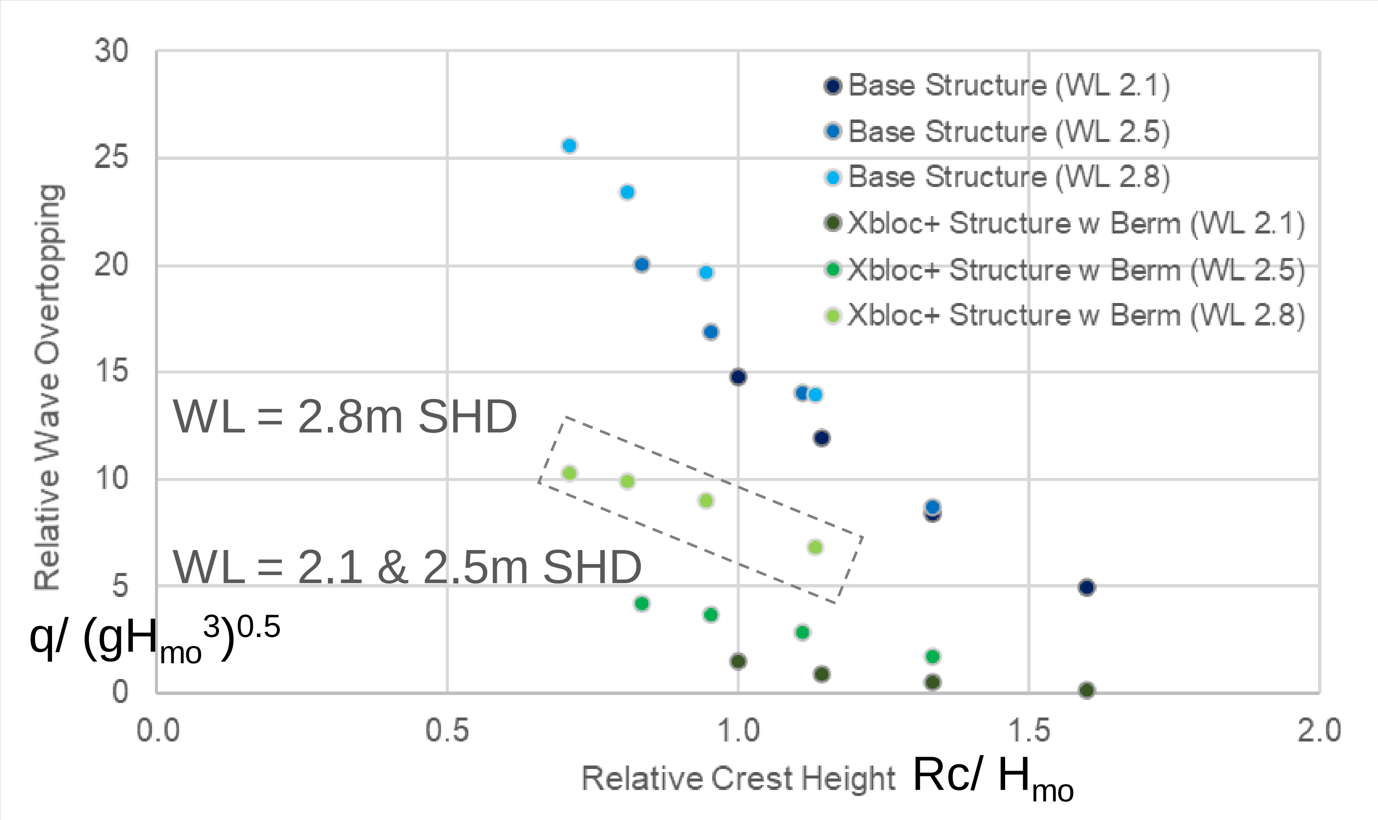
Experimental Result & Discussion (Xbloc+ Structure w Berm)

Delta Marine Consultants

Wave Overtopping Comparison

- Presence of Xbloc+ armour on lower slope with berm structure significantly reduces the wave overtopping: (cf. unprotected structure)
  - by 90% to 98% for lower water level with freeboard 2.4m
  - by 78% to 80% for lower water level with freeboard 2.0m
  - by 51% to 60% for higher water level with freeboard 1.7m

- Xbloc+ proven as effective single-layer, regularly-placed, interlocking coastal protection system
- Berm structure is more effective when water level is closer to its elevation



(slow-motion for WL 2.1m SHD, Hs 1.8m)

- wave breaks at lower Xbloc+ slope as plunging jet

(example video for WL 2.1m SHD, Hs 2.4m)

- Xbloc+ & berm more effective in wave breaking at lower water level

(example video for WL 2.8m SHD, Hs 2.4m)

- less effective wave breaking, run-up jet pushed up-slope

Delta Marine Consultants

Hydraulic Stability Assessment

- Low-crested Xbloc+ structure (lower slope of berm structure) is envisaged to be stable

(before WL 2.1m, Hs 1.5m)

(after WL 2.1m, Hs 1.8m)

(after WL 2.1m, Hs 2.1m)

(after WL 2.1m, Hs 2.4m)

- at WL 2.5m & 2.8m SHD:
  - no displacement, no settlement, no rocking
- at lowest WL 2.1m SHD where wave breaks closest to structure crest:
  - minor displacement of armour observed – remains stable and not considered damage
  - no settlement, no rocking

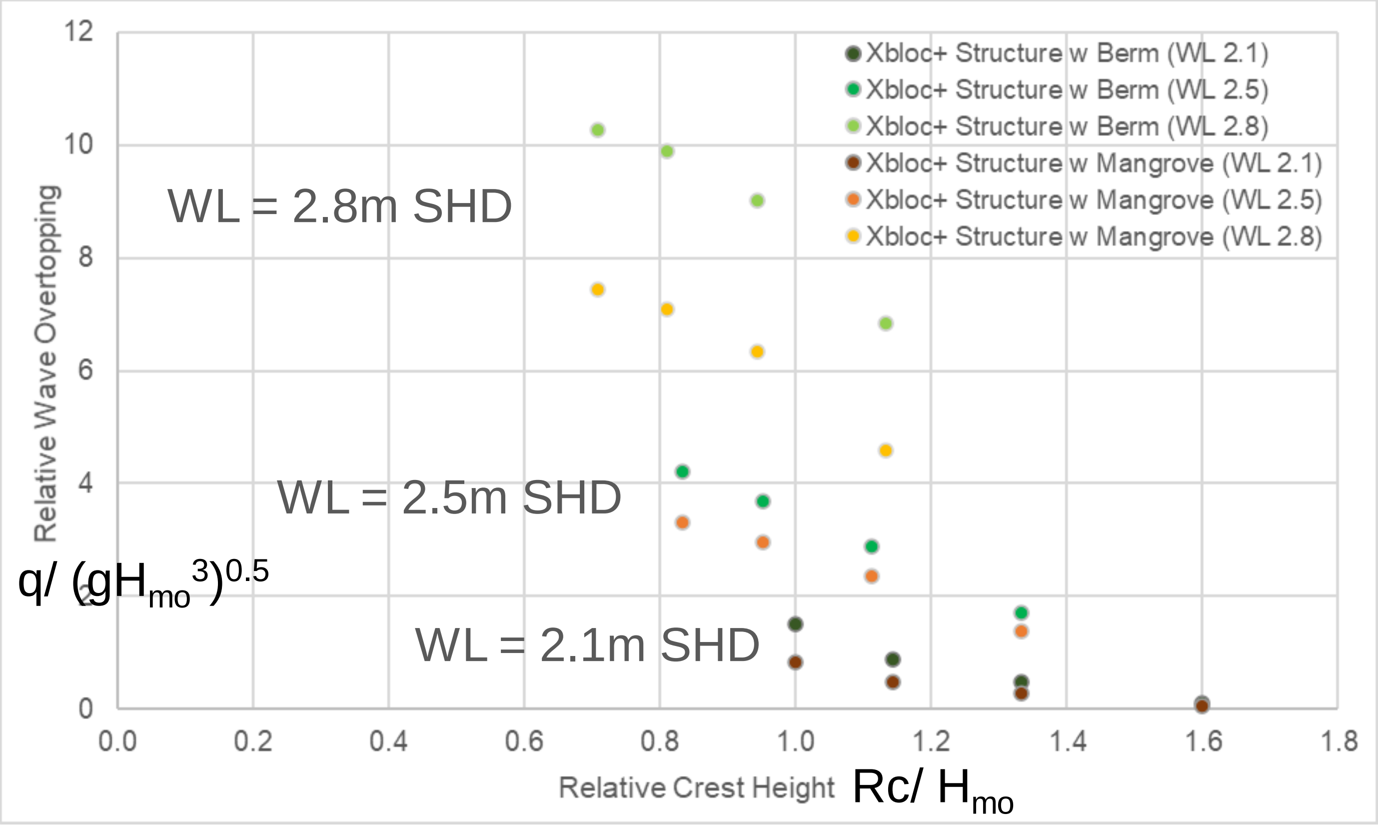
Experimental Result & Discussion (Xbloc+ Structure w Mangrove)

Delta Marine Consultants

Wave Overtopping Comparison

- Presence of mangrove further attenuate the wave through roots of partial submergence and higher roughness: (cf. berm structure without mangrove)
  - by 40% to 45% for lower water level with freeboard 2.4m
  - by 18% to 21% for lower water level with freeboard 2.0m
  - by 28% to 33% for higher water level with freeboard 1.7m

- Mangrove provide more effective wave dissipation with higher root emergence at lower water level
- Where berm structure alone is particularly not effective at high water level, mangrove submerged root induce more interaction for wave dissipation



(slow-motion for WL 2.5m SHD, Hs 2.4m)

- propagation of broken wave and diminish through mangrove root

(example video for WL 2.1m SHD, Hs 2.4m)

- at lower water depth, wave propagate through mangrove root zone

(example video for WL 2.8m SHD, Hs 2.4m)

- at higher water depth, while wave propagate over / above mangrove, submerged root increase the berm influence

Experimental Result & Discussion (Multi-Line Defense – with Upper Xbloc+)

Delta Marine Consultants

- When climate worsen with sea level rise and extreme surge/ wave occurrence, hybrid structure with its multiple line of defense strategy can easily be adapted for upgraded protection.
- Presence of Xbloc+ armour on upper slope of hybrid structure acts as additional defense line:
  - 95% overtopping reduction for highest WL 2.8m SHD and Hs 2.4m (cf. w/o upper xbloc structure)

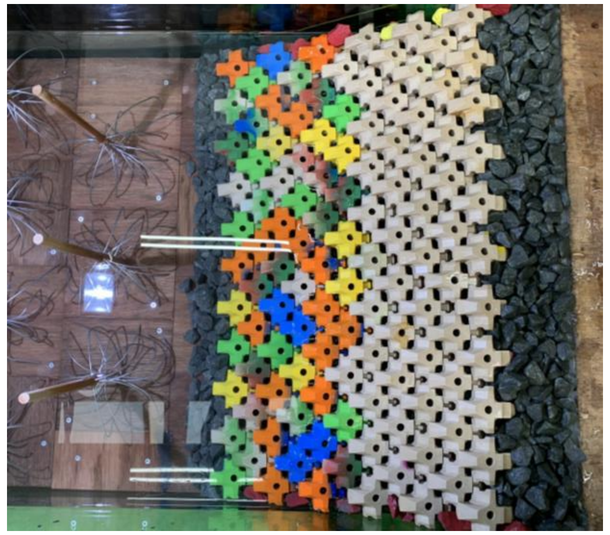
(1st line of defense – xbloc+ on lower slope)

(2nd line of defense – berm structure with mangrove)

(3rd line of defense – xbloc+ on upper slope)

(example video for WL = 2.8m SHD, Hs = 2.4m)

- upper xbloc+ further attenuate the wave
- much reduced reflected wave & overtopping



- where needed, Xbloc+ armour can be incrementally added-on extending to higher crest

(zoom-in upper Xbloc+ view)

- To achieve similar overtopping discharge, a simple 1:2 structure protected entirely by Xbloc+ armour needs to be raised by 1m to have structure crest of 5.5 mSHD.

- Hybrid structure bases on Xbloc+ armour offers robust protection with adaptive features, build only when required

- Combining Xbloc+ with XP-Overtop units on upper slope:
  - 60% overtopping reduction can be further achieved for highest WL 2.8m SHD and Hs 2.4m (cf. xbloc+ armour only)


(zoom-in slow-motion for upper XP-Overtop)


(example video for WL = 2.8m SHD, Hs = 2.4m)

  - incoming wave run-up and deflected backward by the recurve feature of XP-overtop

- Replacing top 2 rows of armour with XP-Overtop is as effective as raising the structure crest (by 1 additional row of Xbloc+) for overtopping reduction

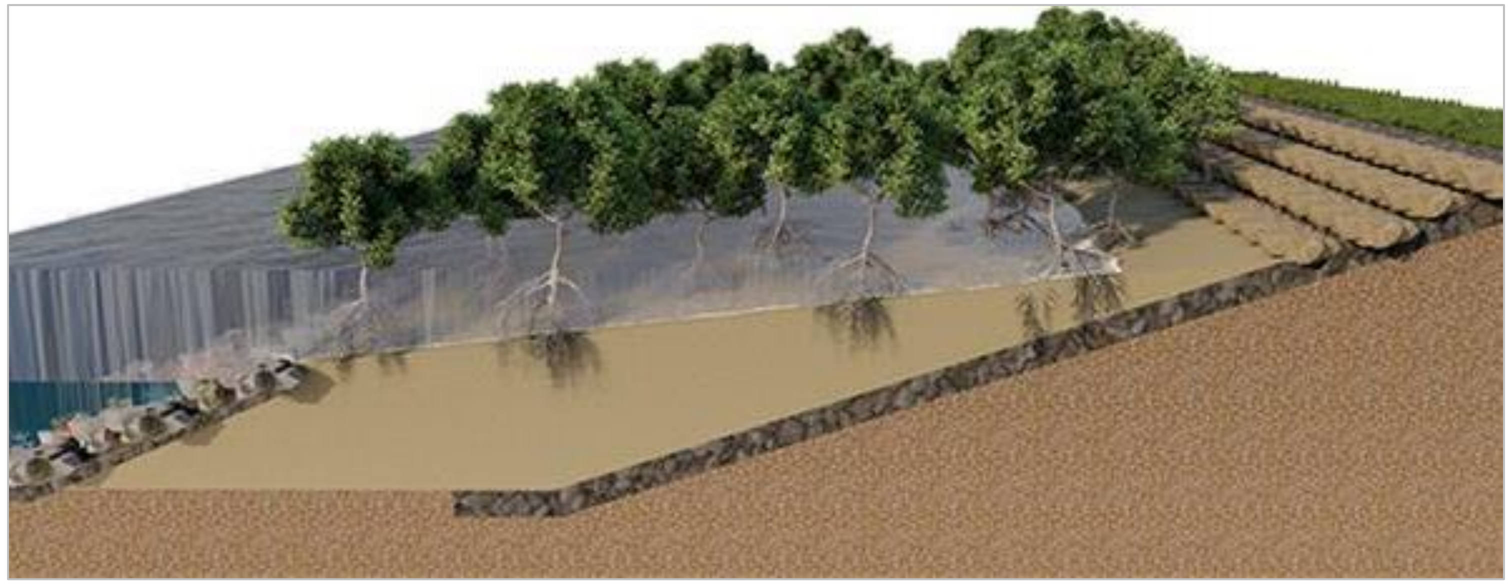

(XP-Overtop armour & its recurve feature)


(zoom-in top view)

Conclusion

Delta Marine Consultants

- Integration of green and grey structure provides additional benefit and serves multi-function purpose
- Xbloc+ product is demonstrated as effective measure for integration as hybrid protection
  - presence of Xbloc+ on lower slope of berm structure reduce the wave overtopping by 51% - 98% (compared to unprotected structure)
  - presence of mangrove reduce the wave overtopping by 18% - 45% (compared to berm structure without mangrove)
- Flexibility and resiliency of Xbloc+ product is demonstrated in preparing the structure for future extreme climate
  - presence of Xbloc+ on upper slope of hybrid structure (as additional defense line) reduce the wave overtopping by 95% for highest tested WL and Hs (compared to w/o upper xbloc+ structure)
  - combined with XP-Overtop on upper slope of hybrid structure, overtopping reduction of 60% can be further achieved for highest tested WL and Hs (compared to xbloc+ armour only)
  - Xbloc+ armour can be added-on extending to higher crest where needed



Build with Nature –

Adaptive Protection for Mangrove Coast

(Chim Yan Qi, Bas Reedijk, Dan Friess, Yang Zi Qian, Santosh Kumar)

Delta Marine Consultants

Background

Delta Marine Consultants

- Mangrove plays significant role in climate change adaptation (coastline stabilization & storm surge reduction function) with additional ecological / social benefit
- Particularly important for Southeast Asia countries, which contains ≈ 35% of the world's mangroves
- Mangrove can adapt to sea level rise and changes in climate (with suitable biophysical condition), and potential for recovery following storm event
- However, due to anthropogenic causes such as land use change, and natural causes such as extreme weather events and erosion, mangrove still decline across the world at rate of at least 0.13% per year (Goldberg et al., 2020)
- Challenges of mangrove rehabilitation/ restoration:
  - sediment balance disturbed by conventional mitigation measure (e.g., hard protection measure)
  - low survival rate from mangrove planting project – mangrove seedling swept by current, or planted at wrong elevation

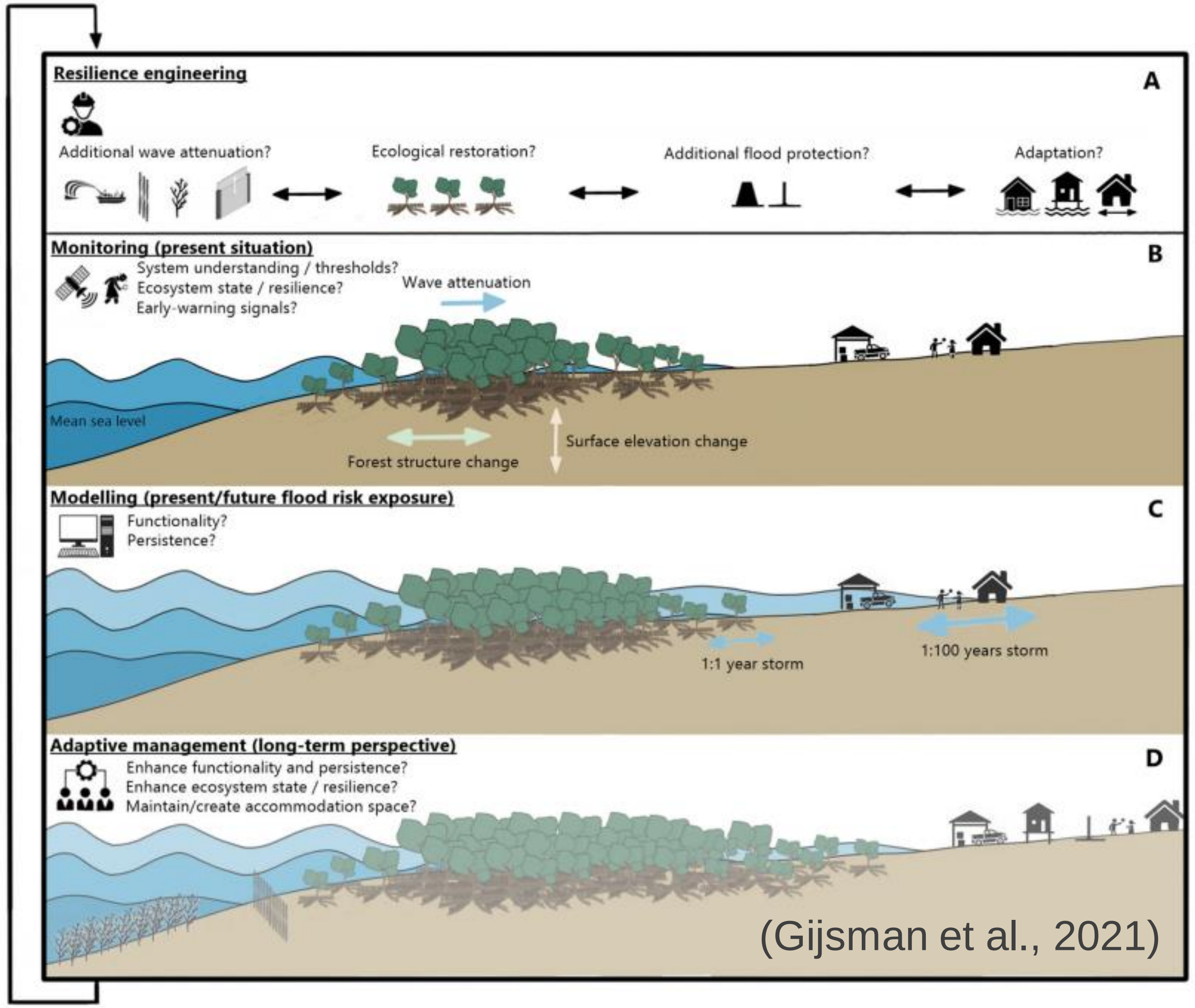
for small and more frequent storm, nature-based solution is most effective (with co-benefit and natural resilience)

mangrove root anchor in soil, prevent erosion, and provide protection during storm event

(source: Mongabay)

(Mandai mangrove & mudflat, *source: NParks*)

Adaptative Management Approach



(Gijsman et al., 2021)

- temporary engineering intervention
  - reduce tree damage / support seedling establishment
  - changing environmental condition to below threshold value, thereby enhancing mangrove functionality and persistence
- continuous monitoring
  - mangrove state and threshold
  - external stressor (e.g. storm and sea level rise)
- continued improvement
  - assessment on mangrove functionality and persistence
  - necessity of (temporary) engineering intervention
- long-term perspective to reduce coastal flood risk with mangrove

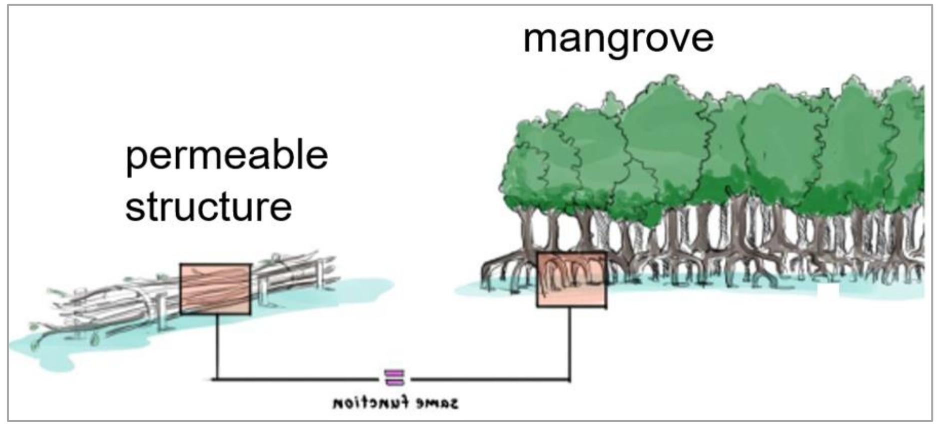
(Xstream – 30 to 40cm height, smaller size of Xbloc)

- In this study, we present a combined engineered approach with nature to enhance mangrove protection:
  - shield replanted mangrove seedlings before they mature
  - stabilize littoral drift to restore low survival rate from mangrove planting project
- An innovative permeable structure is achieved with Xstream system

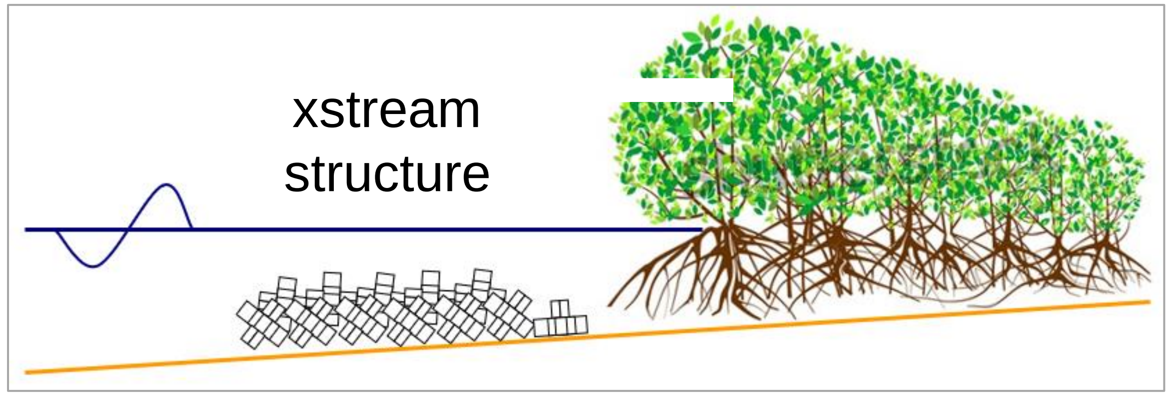
Engineered Approach with Nature

Delta Marine Consultants

- Conventional permeable structure for mangrove restoration (e.g. wood, bamboo, geotextile):
  - difficult to adapt to climate change (not flexible to heighten/ lengthen)
  - easily damage during construction (e.g. deteriorate by sharp object/ shipworm)
  - different material/ component to construct (e.g. connecting wire, horizontal beam, netting)



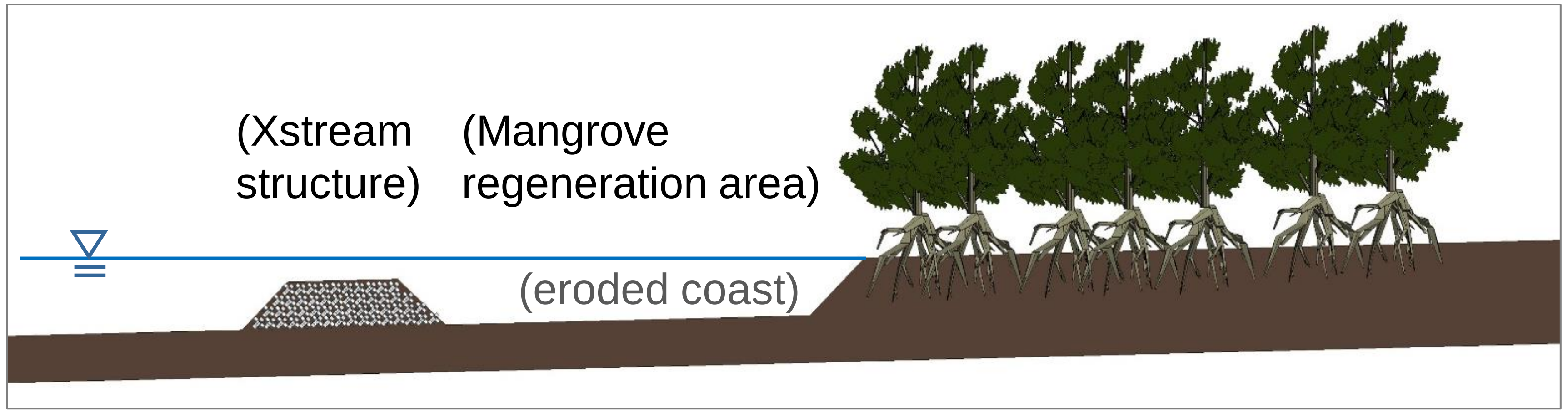
- Our flexible Xstream structure:
  - adaptable to changing seabed level/ scour hole
  - flexible to lower/ heighten/ shorten/ lengthen
    (when needed for sediment steering/ due to climate change)
  - made of only one material, interlocking Xstream blocks



- More advantages of Xstream structure:
  - steep slope possible up to 1:1 with interlocking
  - placed directly on seabed, no geotextile
  - no transition – easy and less maintenance
  - permeable structure up to 60% porosity
    – absorption of wave energy
    – less flow concentration around head
    – shelter for habitat
  - simple construction
    – transported and placed in bulk
    – fast construction to define outer profile

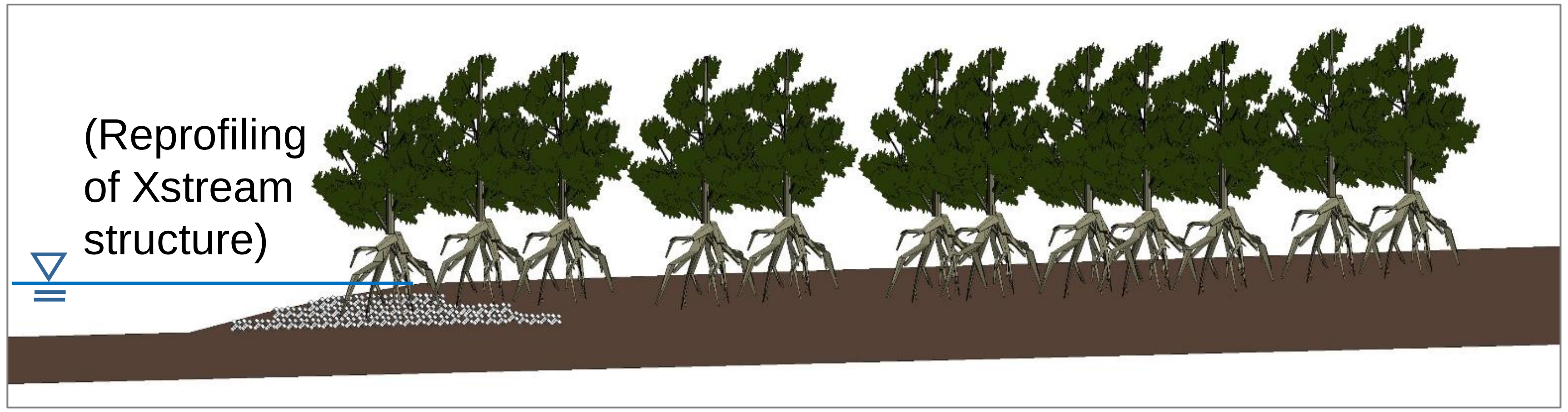
Conceptual sketch of Xstream structure for mangrove coast protection:

- initial stage



- Xstream blocks placed close to coast at suitable distance from mangrove toe
- Xstream serves to reinforce stabilization and support the coastline
- Xstream covered with suitable mud, placed such that sediment will pass through/ over and accrete behind structure to encourage mangrove growth

- after mangrove rehabilitation (longer term)



(Xstream structure support coastline and dissipate part of wave energy)

(matured mangrove withstand storm and dissipate remaining wave energy)

- when erosion process is managed and coastline is accreted to adequate elevation, new mangroves colonize and grow as self-sustained ecosystem
- new mangrove belt break wave and capture sediment naturally
- mangrove colonize towards seaward, Xstream block is expected to reprofile over time and cover the seabed
- collaboratively, mangrove is expected to naturally grow along and in between reprofiled Xstream

Flexible Xstream Structure

<u>Pilot Study – Xstream as Flexible Groyne</u>

- A pilot study is conducted in Netherlands IJssel river to apply Xstream as flexible groyne to protect the riverbank from erosion
- This establish a good picture of how Xstream system function and can help with the integration with nature landscape
- Monitoring of Xstream following the construction of the flexible groyne structure observe that:
  - Xstream groyne structure remains stable
  - No significant bank erosion/ local scour is induced
  - Nature integrating with technical groyne
  - Xstream is expected to take over function of traditional groyne with
    – reduce current velocity, sediment steering
    – more flexibility, adaptability and easier maintenance

<u>Conclusion</u>

- Conceptual feature of adaptive protection for mangrove coast is demonstrated with flexible Xstream structure
- As highly porous protection structure in sheltered coastal environment, Xbloc/ Xstream structure can absorb moderate wave energy and protect the marine environment behind it
- Due to flexibility of Xstream structure, it can easily adapt to seabed change
- For combined engineered approach to work, protection structure need to be designed to incorporate growth requirement of mangrove (species-specific wave energy and tidal inundation threshold), and to utilize coastal protection and other mangrove ecosystem service

Floating Structures

(Next Generation Sea-Level-Rise-Proof Development)

(Jayce Tang Chai Hwa, Mark Keijzers, Bas Reedijk, Leon Groenewegen, Yang Zi Qian)

Delta Marine Consultants

Background

Delta Marine Consultants

- Floating structure is one of the innovation in urban adaptation to:
  - adapt our infrastructure to climate change (counter sea level rise and fluvial flooding)
  - tackle spatial planning from space and population pressure
  - revitalize and expand urban landscape
  - add multi-function/ recreational/ ecological/ resilience value

opportunity for radical adaptation on new urban development

- Floating structure could be the next solution for urban development against climate change, be it for:

(offshore)

- Wind Turbine, England

(industrial)

- Floating Data Centre Module, Singapore

(commercial/ recreational)

- Floating Pavilion, Singapore

(residential)

- Floating Swimming Pool, Singapore

(above DMC projects)

(also for port/ harbour, airport, data centre, oil & gas storage, sea barrier, domestic housing etc)

  - potential as self-sustained development at densely-populated flood-prone coastal area
    – operate on alternate renewable energy resource, mobile – option to relocate in case of anticipated coastal disaster

More Application Examples – Multi-functionality of floating Development

Delta Marine Consultants

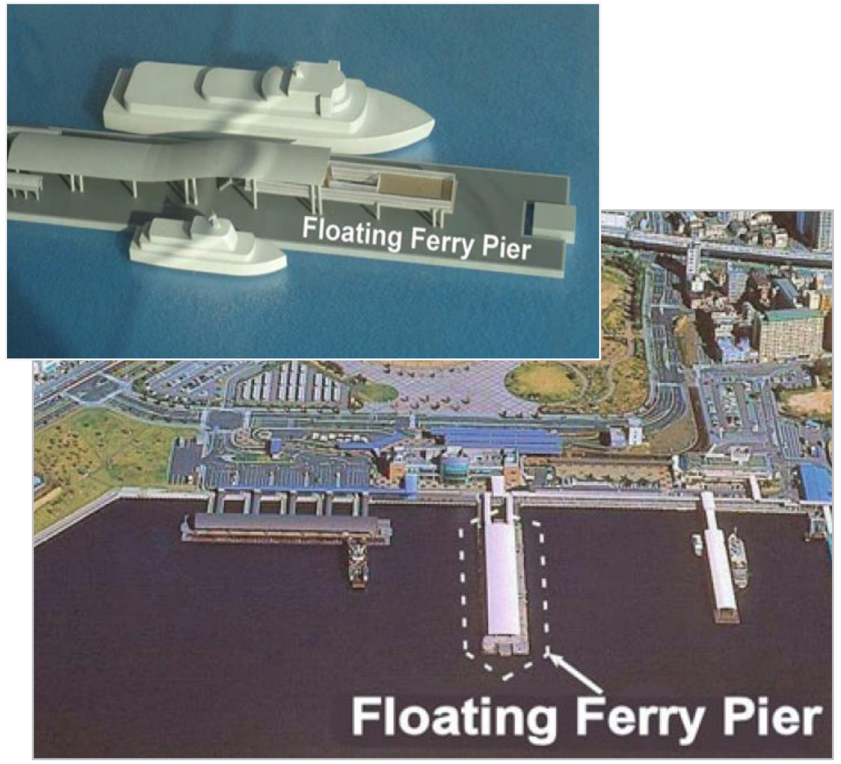
The Okanagan Lake
Floating Bridge, Canada

Floating Road, Hedel, Netherlands

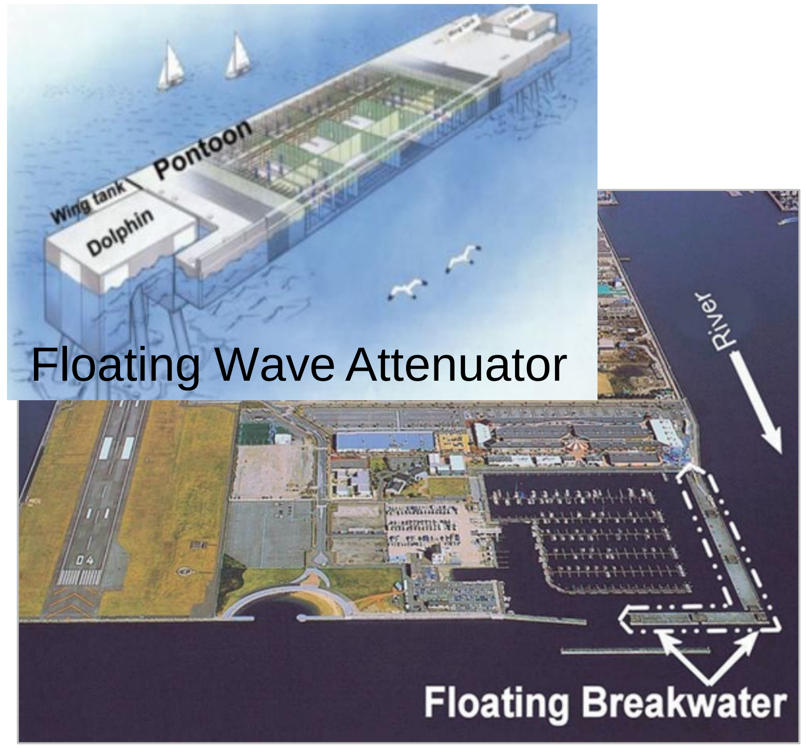
Floating Neighborhood,
Amsterdam, Netherlands

Maldives Floating City
(world’s first true floating island city)

multi-functionality of
floating development



Ujina Floating Ferry Pier, Japan



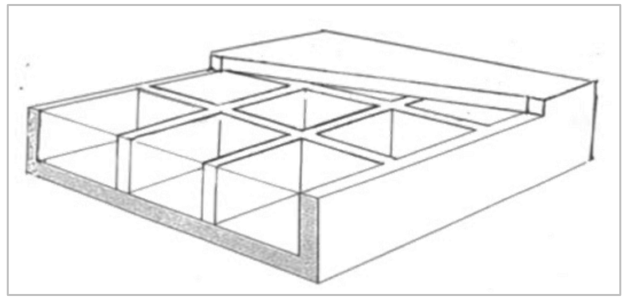
Kan-On Floating Breakwater, Japan

Floating Solar Farm, Singapore

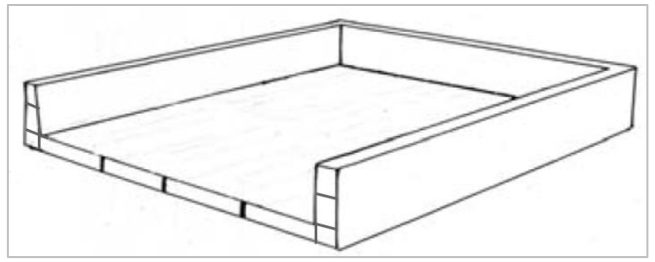
Marina Floating Stage, Singapore

Floating Structure Main Component

- **Floating Hull Structure**
  - Typical hull material – concrete/ steel
  - Floating body module design can vary

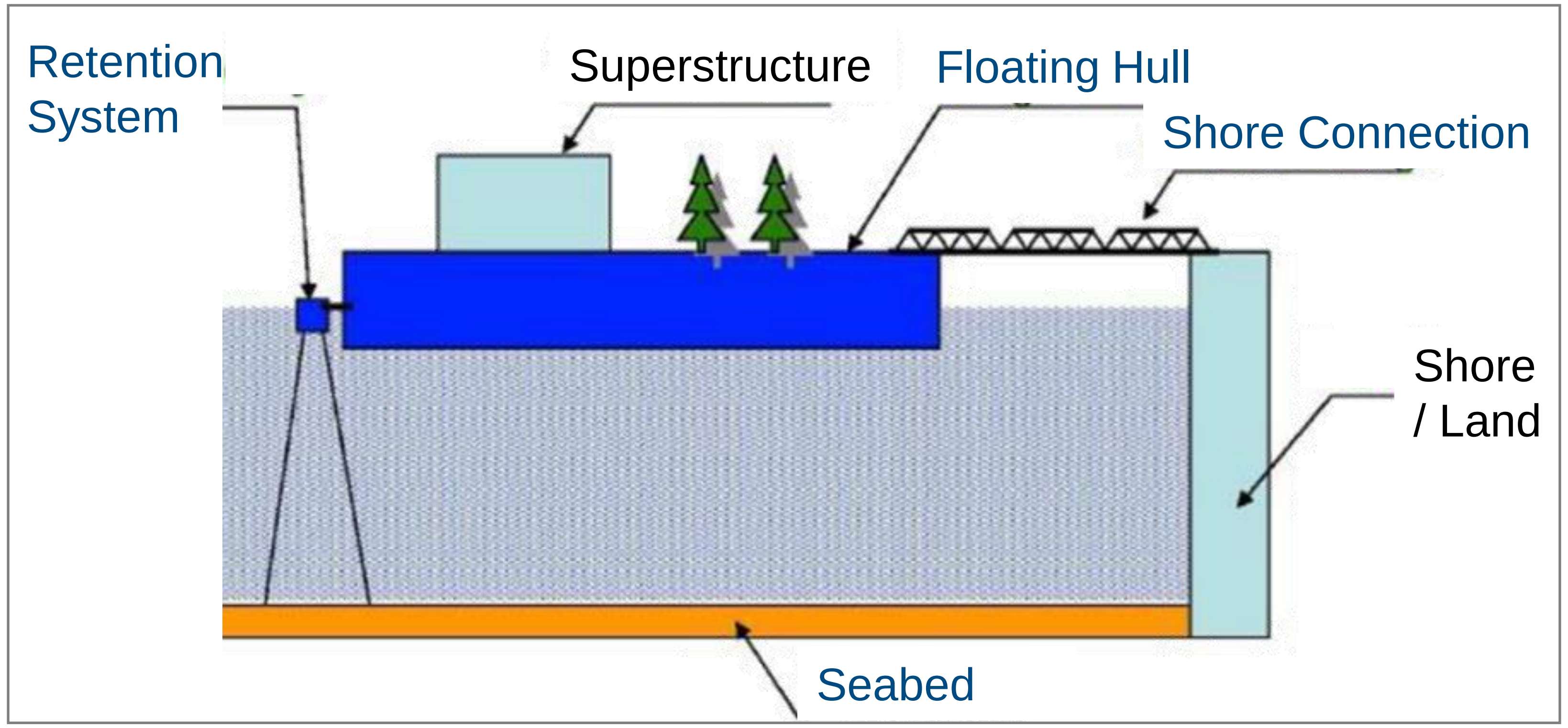


(Box Type, Standard Caisson)

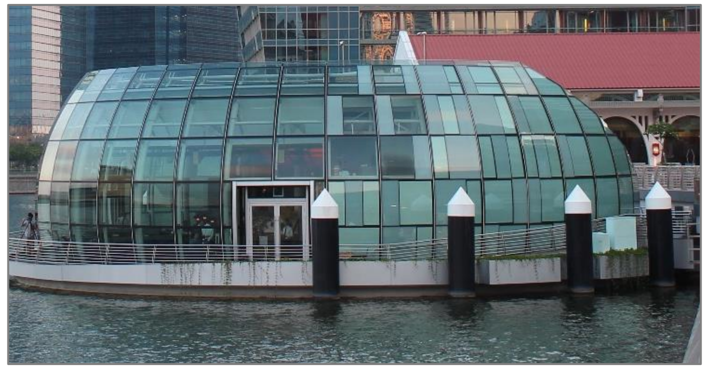


(Double Hull Type)

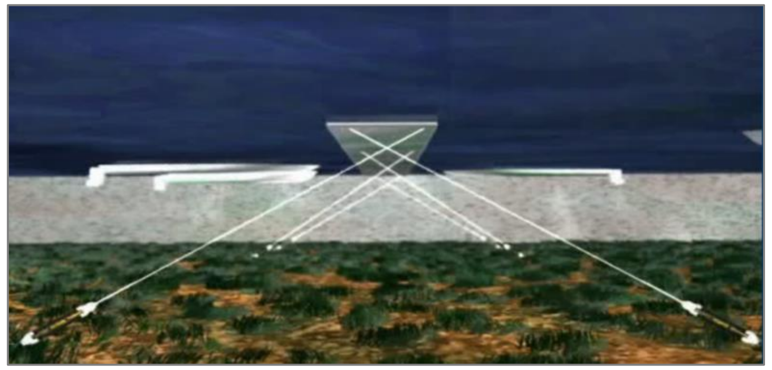
  - Compartment can be utilized for ballast system to accomplish stability of floating structure



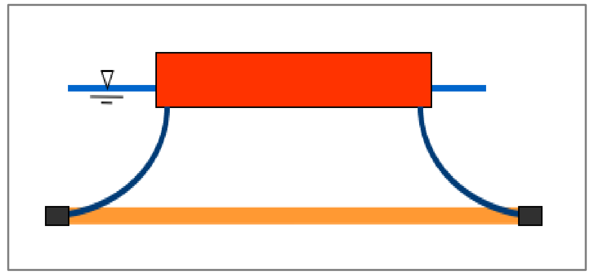
- **Retention System**
  - Ensure floating structure kept in position
  - Prevent structure from drifting away but allow moving up & down according to tidal/ ballast change
  - Options for retention system: (selection depending on site condition, design forces and allowable motion)



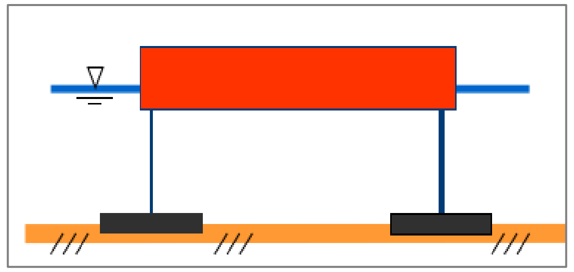
(Retention Pile)



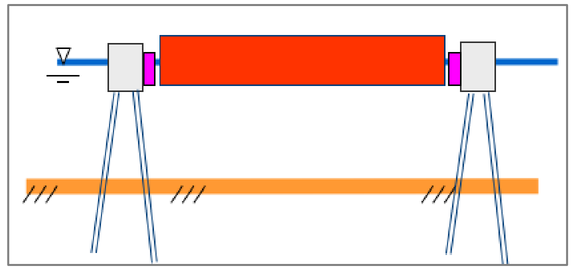
(Tensioned Cable)



(Chain, Rope, Anchor & Sinker)



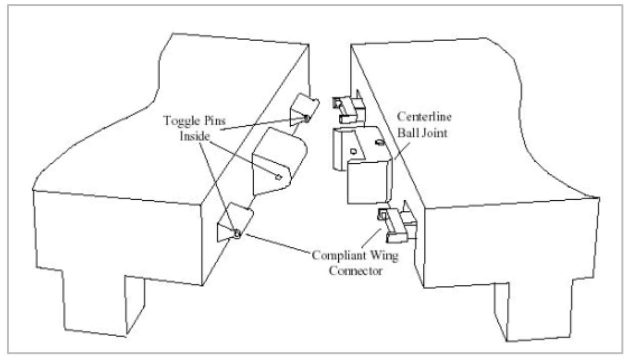
(Tension Leg)



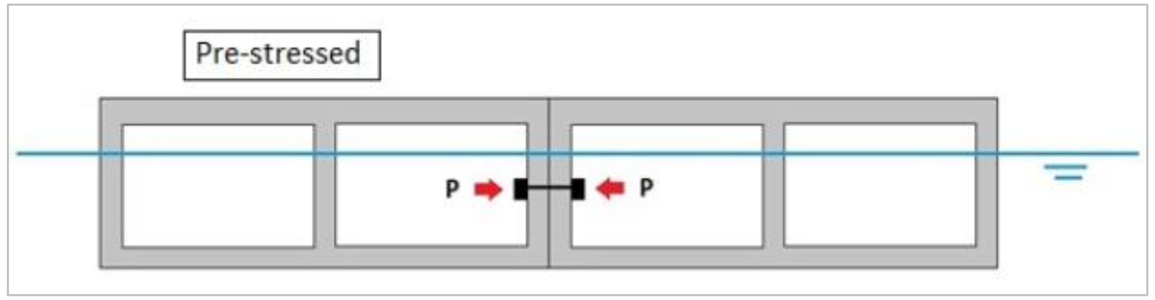
(Jacket, Pile & Fender)

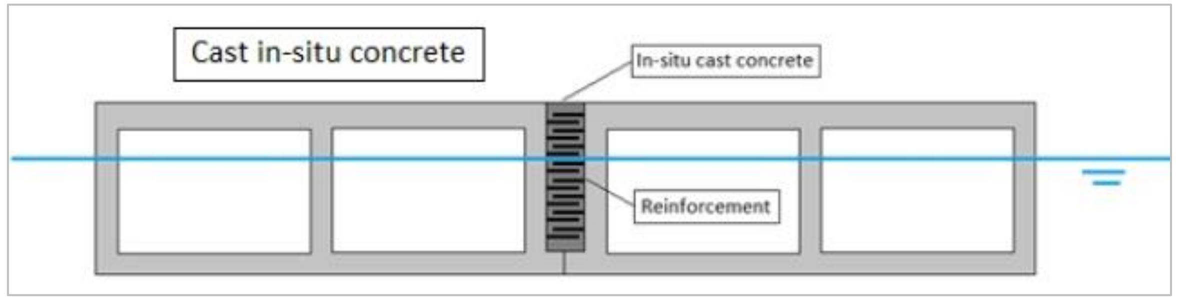
Floating Structure Main Component

- **Module Connection**
  - For modular floating structure to act as single integrated unit
  - Critical for global structure safety and for efficient assembly & marine operation
  - Failure of one connection shall not jeopardize floating stability and safety of adjacent modules, nor integrity of global structure
  - Common type of connections used in practice: fully flexible, vertical free, hinged connection, fully rigid connection



(Hinged Connection)

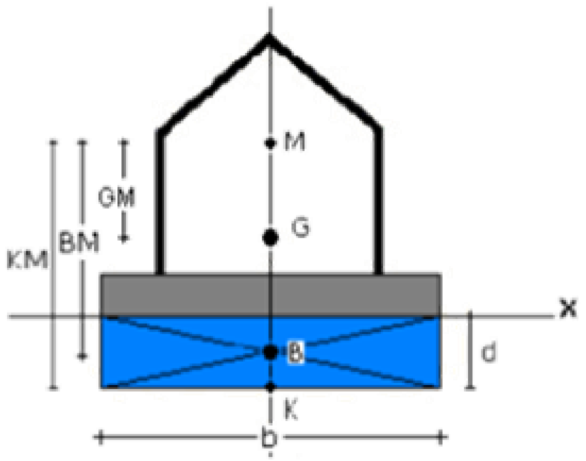




(Fully Rigid Connection)

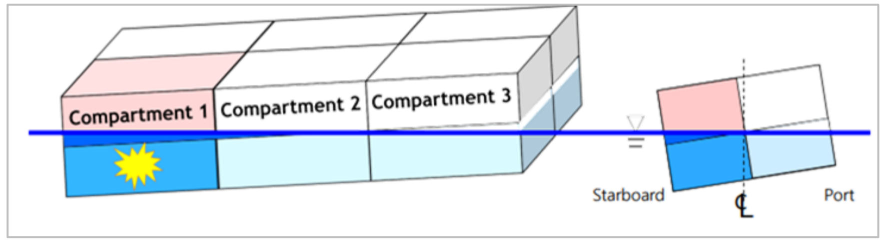
Key Points to Take Note

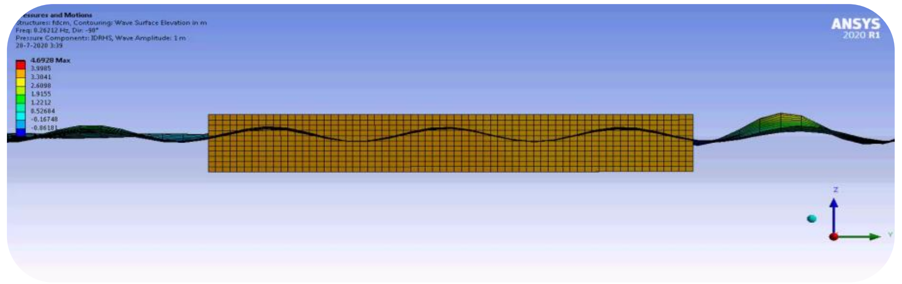
Floating Stability



(metacentric height)

- must be statically and hydrodynamically stable during full design life
- to consider possible extreme load cases
- to check damage stability,
  e.g. flooding in one or certain numbers of compartments shall not cause overtopping of floating structure
- to minimize motion effect and acceleration to create comfortable environment





Key Points to Take Note

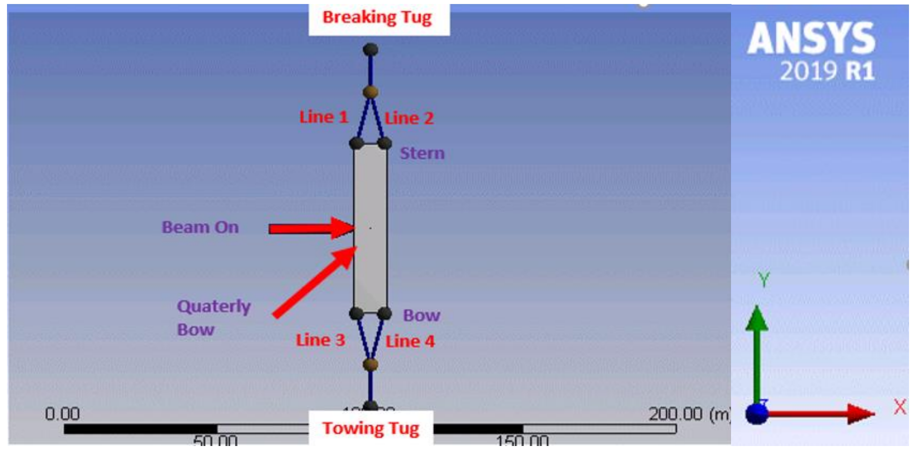
Delta Marine Consultants

Watertightness

(For Concrete)

- watertightness achieved by ensuring minimal compression zone in concrete section, by post-tensioning or provide liner
- concrete mix design
- quality control during execution to avoid poor workmanship

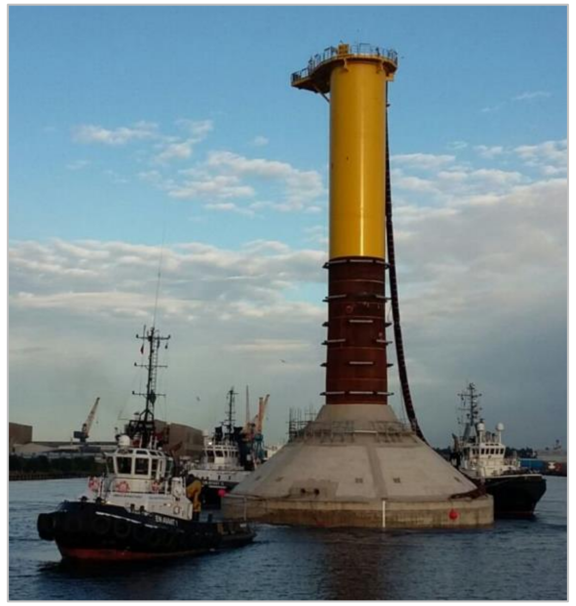
Module Transportation



- for transport of floating module from construction site to final destination, towing plan and analysis shall be conducted to ensure floating structure sustain environmental condition and forces encountered during towing process

New Type Crossing Project, by DMC
(Float and Submerge during Construction)

Fehmarnbelt Tunnel Project, Germany by *DMC*
(Float and Submerge during Construction)



Wind Turbine Project, England by *DMC*
(Float and Submerge during Construction)

Challenges & Conclusion

Delta Marine Consultants

Challenges

- Legislation and Regulation
  - For large scale concrete floating structure to be implemented in nearshore of Singapore, immediate question raised would be “should floating solution be considered a vessel or building?” as this determine the application of design code and regulation to follow
  - Room for optimization on current building design guidelines & codes for nearshore floating structure development
  - Authorities' engagement in early stage & throughout design/ construction process required to arrive at mutually accepted solution
- Public Perception and Investment
- Environment/ Ecology
- Technology and Scale

Conclusion

- Gifted with relatively benign sea state condition with minor threat from tsunami and typhoon, building floating structure in Singapore water is a feasible engineering solution
- Floating structure is multifunctional and flexible for relocation and expansion
- With its highly adaptive nature to sea level rise, we envision floating structure will be the next generation sea-level-proof development

(DMC projects)

Conclusion

In building climate-resilient coast, integrated planning for coastal adaptation is necessary:

- Greater focus on innovative hybrid and flexible approach for coastal protection, combining with natural system where appropriate
  - co-benefit (ecological / environmental / social) besides coastal protection
  - robust protection, capitalizing both built and natural infrastructure
  - allow innovation and better integration in coastal protection design
- Floating structure as versatile solution for urban development against climate change with multi-functionality for sheltered coastline
- Adaptive and flexible coastal protection design in view of climate change uncertainty
- Constant review / update of adaptation planning with continued innovation on protection approaches