

INTEGRATED SOLUTIONS FOR RISING SEA LEVEL

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ABSTRACT: One of the major challenges facing coastal cities is sea level rise and urban flooding caused by climate change. Protection of coastal cities from adverse impacts of sea level rise is a resource demanding task. Geotechnical engineers can play a pivotal role in developing cost-effective solutions to reduce the cost involved and maximize the benefits. One of the options to achieve a high cost-effectiveness is through an integrated design by integrating coastal protection systems with other developments including space creation, flood control, clean water, infrastructures for transportation and marine ecosystem restoration. One of the integrated solutions developed at Nanyang Technological University is presented. This solution involves the construction of seawalls together with the formation of coastal reservoirs for water catchment for flood control and for clean water supply, land reclamation to create space and measures to preserve or restore the marine ecosystem. Methods for the construction of seawalls, land reclamation using clay slurry and methods for incorporating the eco-engineering elements will be discussed in this paper.

KEYWORDS: Climate change, Coastal protection, Coastal reservoir, Land reclamation, Marine ecosystem, Seawall construction.

1 INTRODUCTION

Climate change has emerged as one of the most critical global challenges affecting profoundly both natural ecosystems and human societies. One of the most visible and concerning consequences is the ongoing rise in global sea levels. In Singapore, the mean sea level (MSL) has increased by approximately 14 cm since the 1970s, and projections suggest that this rise could reach up to 1.0 m by Year 2100 (Cannaby et al., 2016). This trend poses significant threats to low-lying coastal areas, particularly urban centers where infrastructure, economic activity, and population density are concentrated. Coastal cities are increasingly exposed to hazards such as tidal inundation, storm surges, and saltwater intrusion. These risks are intensified by the growing frequency and severity of extreme weather events driven by climate change. Urban flooding—both coastal and inland—has become a recurrent issue with high economic and social costs. Contributing factors include aging drainage infrastructure, the loss of natural buffers such as wetlands, and rapid urban expansion. The interaction between rising sea levels and urban development has led to complex flood dynamics that require forward-thinking and multi-disciplinary responses.

To safeguard lives, infrastructure, and ecosystems, the development of robust coastal defense systems is essential. Traditional hard-engineering solutions—such as caisson seawalls, breakwaters, or earth dams—when constructed alone, are often expensive in relatively deep waters and can sometimes be detrimental to the environment due to large-scale earthworks (Chu et al., 2009; Chu et al., 2009b; Yan et al., 2009; Taku, 2013; Yeung, 2016; Vousdoukas et al., 2020). Furthermore, rigid defenses can disrupt coastal hydrodynamics and sediment transport, sometimes worsen shoreline erosion or lead to catastrophic consequences if they fail (Pranzini et al., 2015). Nature-based solutions, including mangrove forests, seagrass beds, and coral or shellfish reefs, offer alternative forms of coastal protection. These systems provide ecological benefits while dissipating wave energy and stabilizing sediments. However, they are generally limited to shallow waters, exhibit seasonal variability, and are vulnerable to climate change and human activities (Morris et al., 2018). As such, neither hard nor soft approaches alone can provide comprehensive, resilient protection in all coastal environments. There are growing needs for integrated and adaptive coastal defense systems that

combine the strengths of both traditional engineering and resilient strategies. This approach promotes sustainability, cost-effectiveness, and multifunctionality.

This paper introduces an integrated coastal defense solution developed at Nanyang Technological University, Singapore. The system features a multifunctional seawall combined with a coastal reservoir, which not only mitigates flooding but also serves as a freshwater source. Land Reclamation can be incorporated into the formation of coastal reservoirs. Eco-engineering elements are also incorporated, such as the intertidal zone, grassland or mangroves. This integrated solution offers a resilient and adaptable strategy for coastal cities like Singapore. The model is also scalable and applicable to other urban coastal regions facing similar pressures from climate change and rapid urbanization.

2 INTEGRATED SOLUTIONS

Singapore is vulnerable to climate change and sea level rising, and it also faces critical challenges in water scarcity due to its growing population and increasing demand for freshwater. An integrated solution to address all these issues would be more cost-effective. For flood control and clean water, the use of coastal reservoirs has been proposed (Yang et al., 2012). The seawall is the most important part of the solution. Given the extensive need for seawalls to protect coastal areas, the solutions for seawalls should not only reduce construction costs but also be adaptable to sea-level rise and allow flexibility for future redevelopment.

One example of an integrated design is the coastal protection system for the East Coast of Singapore as shown in Fig. 1. It consists of seawalls, land reclamation and coastal reservoir. The coastal reservoir can function as an urban runoff catchment, reducing flood risk and supplying clean water. The seawall serves as a coastal defense system. It also forms the containment bund for land reclamation and coastal reservoir. The wall for land reclamation needs to be rigid to sustain the earth behind. The seawall for the reservoir serves mainly as a separation of the seawater from the water in the reservoir. As there is water on both sides, the seawall for the coastal reservoir does not have to be a rigid gravity type. It is possible to design it as a flexible seawall as shown in Figure 2 (Chu et al., 2024). The design concepts of both the flexible seawall and suction

caisson wall will be introduced in this paper. In this integrated approach, flexible seawalls present a novel and promising alternative to rigid structures for coastal reservoirs, particularly in Singapore, where tidal fluctuations are minimal and the risks of hurricanes or strong waves are low. However, the land reclamation may result in a series of adverse ecological impacts. The eco-engineering elements—such as grasslands, mangroves, and cropland—can be incorporated into reclamation projects to restore ecosystems, promote soil conservation, gain economic benefits, and reduce environmental impacts (Qiu et al., 2021). This integrated, multifunctional approach aligns with Singapore’s vision for resilient and sustainable coastal infrastructure.



Figure 1. Coastal reservoir as part of an integrated solution for sea level rise

In the following, the design and construction of the three elements of the coastal defence system: seawall for reservoir, seawall for containment bund of land reclamation and the land reclamation will be discussed separately.

3 FLEXIBLE SEAWALL FOR COASTAL RESERVOIR

The proposed conceptual design and original idea of flexible seawall can be illustrated in Figure 3.

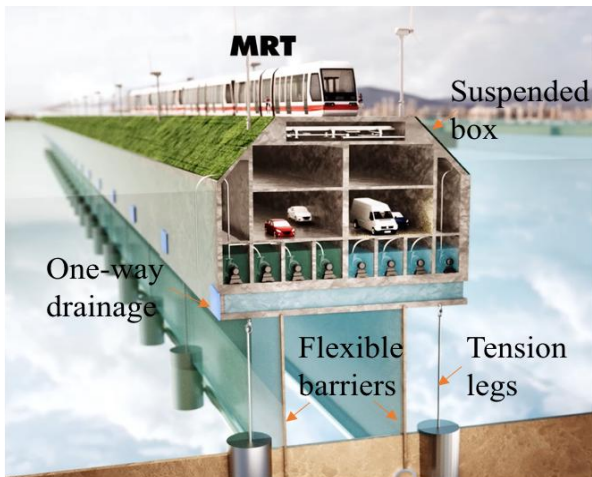


Figure 3. Proposed conceptual design for flexible seawall

The flexible seawall consists of a suspended box at the top, two layers of impervious, flexible barriers below, and seabed anchors. This suspended structure is subdivided into multiple compartments. The lower compartments function as ballast to regulate the stability of the suspended box, while a one-way drainage channel allows water to be discharged from the reservoir into the open sea without backflow (Fig. 3). Vertical equilibrium is maintained through a combination of ballasts, self-weight, tension cables, and seabed anchors. For durability and risk control, two layers of flexible, impermeable barriers are used. While the flexible seawall can be applied in various

water depths, the deeper the water, the greater the saving compared with a conventional concrete gravity wall, which requires more steel and concrete as well as a much stronger foundation.

The flexible seawall shown in Figure 3 possesses the following several advantages over the conventional concrete seawall designs: 1) It is much cost-effective as the usage of sand and concrete is much reduced; 2) its height of the flexible seawall can be adjusted, making it adaptable to sea level rise; 3) as modular designs, the construction of flexible seawalls causes much less disturbance to the surrounding marine ecosystem since massive seabed works or dredging are not required; and 4) The flexible seawall can be reallocated for future redevelopment. Furthermore, the flexible seawall can be designed to enhance environmental restoration and marine ecosystem. Nature-based features can be incorporated to preserve the inter-tidal zone and promote marine biodiversity. As illustrated in Fig. 3, the design allows for slopes on both sides of the wall, creating intertidal zones that support mangroves, seagrasses, and other coastal habitats.

4 SUCTION CAISSON SEAWALL CONSTRUCTION

The seawalls used as a containment for land reclamation have to be a gravity type to sustain the lateral soil pressure behind. Several foundation types have already been used in practice. As there is a thick layer of soft marine clay in the seabed of East Coast, Singapore, suction caisson seawall will be ideal. Another advantage of using suction caisson wall is that it causes the least disturbance to seabed or marine ecosystem. Suction caisson foundations have been used for offshore structures or seawall construction. It possesses several advantages over conventional foundation methods when used in soft seabed (Chu et al., 2012; Guo et al., 2017). As an alternative foundation type, suction caissons have demonstrated the construction or economic benefits for offshore and coastal infrastructure. Furthermore, it takes shorter time to install compared to traditional piles or gravity-based foundations. Suction caissons also offer enhanced adaptability to various subsurface conditions. They can be installed in soft soil profiles with minimal disturbance to the seabed, often without requiring prior ground treatment (Chu et al., 2012). These advantages make suction caissons particularly attractive for deployment in areas with thick layers of soft marine clay or relatively deep coastal waters—common conditions in regions like Singapore.

The design concept, as illustrated in Figure 4, incorporates a modular foundation system comprising four concrete suction caissons. The use of four caissons in a grouped configuration improves both vertical and lateral capacity, and facilitates controlled, uniform settlement by regulating the suction applied within each chamber. The suction caissons and the upper caisson cylinders that form the seawall are fabricated at a casting yard, preassembled, and towed to the site. Installation is achieved by hydrostatic pressure acting externally and suction applied internally. Alternatively, the upper concrete cylinders can be installed atop the suction caissons after foundation installation. Segment joints between the seawall and foundation are sealed using cement grout to ensure structural integrity. To accommodate future sea level rise, taller top caisson segments can be incorporated into the design, offering long-term adaptability for climate resilience.

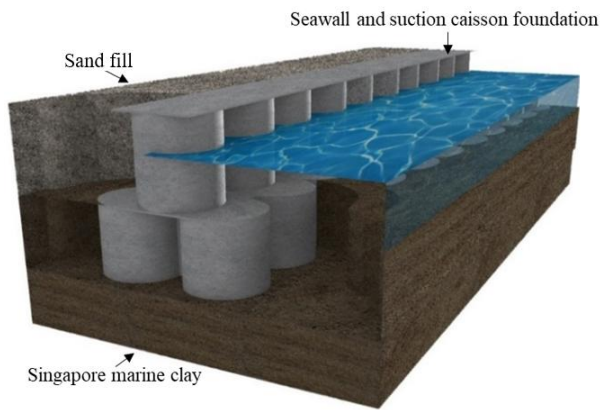


Figure 4. Proposed containment structure using caissons for land reclamation (After Chen et al., 2022)

The suction caisson seawall is proposed as a containment structure for land reclamation projects as shown in Figure 5. The presence of deep marine clay in Singapore and the need for a stable structure in relatively deep water make suction caissons an ideal foundation solution. By using large-diameter suction caissons, the required bearing capacity per unit area is reduced while the lateral resistance is significantly enhanced (Randolph and Houlsby, 1984; Yan et al., 2017). Following the installation of the suction caissons and the caisson seawall, fill materials are placed within the containment structure to reclaim land. This filling process increases lateral earth pressures on the seawall, potentially compromising its stability. To support these lateral forces and enhance lateral stability, various types of ground improvement methods—such as sand compaction piles, stone columns, geosynthetic-encased stone columns, deep mixing columns, or controlled modulus columns—can be installed seaward of the suction caisson foundation (Kitazume et al., 2005; Chai et al., 2009; Gniel and Bouazza, 2010). Another complementary approach involves accelerating consolidation of the soft seabed or fill materials (especially if clay is used) using prefabricated vertical drains or horizontal drainage techniques, thereby reducing pore pressure and lateral load on the structure.

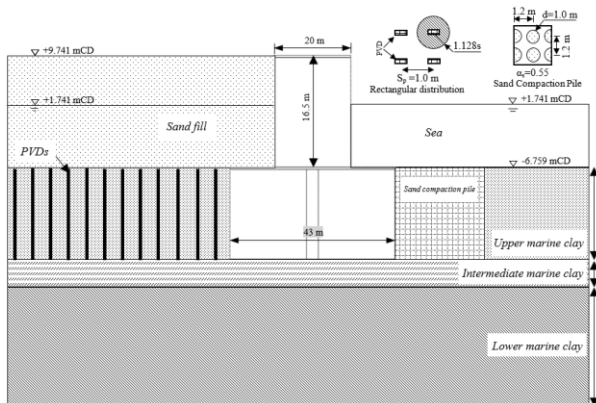


Figure 5 Land reclamation using suction caisson seawalls

5 LAND RECLAMATION USING SOFT CLAY

Due to the environmental impacts associated with sand mining — including riverbank erosion, coastal degradation, and disruption of marine ecosystems — many countries have implemented strict regulations to limit or ban the extraction of sand from rivers and marine sources. As a result, alternative fill materials such as soft or excavated soils, particularly dredged clay slurry within the coastal reservoir, have become alternatives for land reclamation projects, especially in sand-scarce countries like Singapore (Chu et al., 2009a; Chu and

Guo, 2015). However, the use of extremely soft dredged materials presents considerable challenges in consolidation and ground improvement. Traditional methods involving the installation of vertical drains, such as prefabricated vertical drains (PVDs), are often inefficient in very soft soils due to difficulties in maintaining verticality and ensuring proper embedment. To address these limitations, horizontal drains combined with vacuum preloading have been proposed as a more effective solution for consolidating soft fills in land reclamation projects (Shinsha et al., 2014; Chu, 2012; 2016).

A novel solution utilizing horizontal drainage enhanced geotextile (HDeG) sheets has been developed and tested as shown in Figure 6 (Chu and Guo, 2015; Chen et al., 2023). HDeG sheets consist of discrete drainage cores embedded at regular spacing and are bonded with a high-transmissivity geotextile fabric. These geotextile sheets not only serve as horizontal drains but also act as vacuum distribution layers when sufficient transmissivity is ensured. The sheets can be manufactured in rolls, transported to site, and installed in sequential layers as the reclamation process progresses. The installation process begins with the placement of a layer of HDeG sheet on the seabed inside a containment bund using a barge, as illustrated in Fig. 7a. The first layer of dredged clay slurry is then hydraulically placed on top of the sheet, completely covering it. Vacuum pressure is subsequently applied to initiate consolidation (Fig. 7b). Once sufficient consolidation has occurred, a second layer of HDeG sheet is placed atop the newly consolidated layer, followed by another clay slurry layer. This sequence is repeated until the desired reclamation height is achieved. A geomembrane is then installed at the top of the reclaimed area to seal the system (Fig. 7c), allowing continued vacuum consolidation. A surcharge load can be applied above the geomembrane after a certain period to accelerate further consolidation (Chen, 2021). By using this new land reclamation method, the overall vacuum preloading duration can be shortened significantly, and the construction difficulties involved in the formation of working platform will be eliminated.

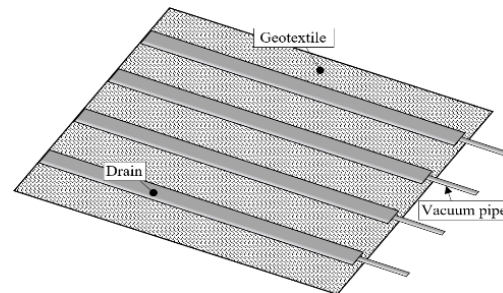


Figure 6. Configuration of horizontal drainage enhanced geotextile sheet (After Chen et al, 2023)

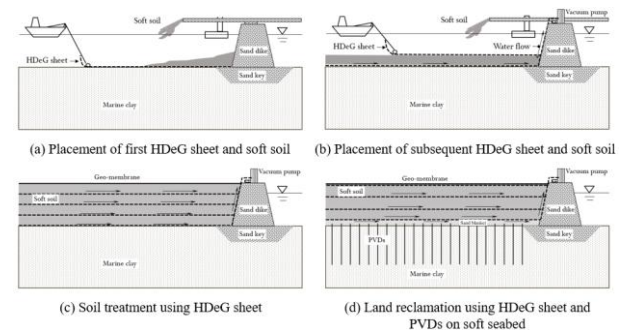


Figure 7. Construction procedure: (a) Placement of first HDeG sheet and soft soil; (b) Placement of subsequent HDeG sheet and soft soil; (c) Soil treatment using HDeG sheet; and (d) Land reclamation using HDeG sheet and PVDs on soft seabed (After Chen et al., 2023)

6 CONCLUSIONS

In response to the challenges posed by climate change and rising sea levels, this paper presents an integrated coastal defense strategy. The proposed integrated solution combines multifunctional seawalls—both rigid and flexible—with coastal reservoirs for freshwater storage and flood control, along with land reclamation supported by innovative geotechnical techniques such as suction caissons and horizontal drainage enhanced geotextile sheets (HDeGs). The flexible seawall, incorporating eco-engineering elements like intertidal zones, not only reduces environmental impact but also promotes biodiversity and long-term resilience. The resilient design of the flexible seawall makes it adaptable to sea level rise. This integrated approach highlights the critical role of geotechnical engineering in contributing to climate-resilient, cost-effective, and multifunctional coastal infrastructure, offering a promising solution for cities worldwide that face the dual pressures of climate change and rapid urban development.

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