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"Adapted mangrove on hybrid platform" – Coupling of ecological and engineering principles against coastal hazards

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A R T I C L E I N F O

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A B S T R A C T

Mangrove forests are expected to act as green infrastructure against coastal hazards. However, mangroves cannot grow along urban coasts where the water is too deep and the wave is too high. This paper conceptualizes a new disaster countermeasure, coined as "*adaptive mangrove hybrid platform,*" which provides a solution to achieve ecosystem-based disaster risk reduction (Eco-DRR) in urban areas; particularly, those in developing countries. The proposed concept is a hybrid solution, starting from a landfill to level the seabed. A mangrove plantation is then established on the surface. The front part of the landfill is intentionally raised to form a shore-protection mound to reduce wave run-up that may wash away mangrove seedlings. Improvised technology such as wood piles and small stones can also be utilized to protect the landfill from erosion. The platform will inevitably sink owing to self-weight consolidation, land subsidence, and sea-level rise, while sediment deposition trapped by the developed mangrove forest may be the reliable avenue to raise the ground. Hence, the initial geometry of the landfill needs to be appropriately designed in order to achieve an equilibrium state whereby the ground surface is adaptively in balance with the relative sea-level rise. In this paper, many challenges as well as advantages are addressed, with the objective of promoting research to facilitate the exploration of adaptive mangrove hybrid platforms.

Introduction

The advantage of ecosystems is referred to as ecological resilience. The appropriate management and conservation of ecosystems are expected to reduce disaster risk. Mangroves have drawn worldwide attention with regard to ecosystem-based disaster risk reduction (Eco-DRR) or green infrastructure. A number of field surveys conducted after major disasters such as the Indian Ocean tsunami in 2004 and Typhoon Haiyan in 2013 observed the mitigating effects of mangroves against tsunamis and storm surges [1,2]. For example, the Indian Ocean tsunami claimed 468 human lives in six small coastal villages of South India, which were in close proximity to the shoreline at a distance between 0.1 and 0.4 km, without any significant mangrove vegetation cover. On the other hand, no lives were loss in three villages and there was significantly lower number of deaths in four villages (30 deaths). All these villages with lower casualties were situated behind mangrove forests, at a distance of 1–2.5 km away from the shoreline [3]. In the case of Typhoon Haiyan, the interview survey with local residents in Leyte Island of the Philippines revealed that many respondents were aware of and appreciated the role of mangrove forests in protecting their lives and property from the storm [4].

Nevertheless, despite the popular and widely accepted view that mangroves act as living dikes, there is still little evidence available to quantify this hypothesis [5]. For example, it is considered that tree vegetation may shield coastlines from tsunami damage by reducing wave amplitude [6]. However, this is not always the case because tsunami height could even be increased at the front edge of a mangrove forest as a consequence of the resistance posed by vegetation. The disadvantages of coastal forests have also been revealed. For instance, an open gap in a forest may create a strong current through a channeling effect, while floating debris from broken trees can damage surrounding buildings and hurt people [7]. Therefore, the effectiveness of an ecosystem in reducing disaster impacts needs to be scientifically investigated to improve the effectiveness of any potential Eco-DRR application [8].

The establishment of a mangrove plantation is a challenging task. Although there are examples of successful projects, there are many instances of failure. Planted seeds are sometimes lost to the impact of high waves or strong currents (Fig. 1a). A strong tsunami could instantly uproot a mangrove forest (Fig. 1b). Even if the mangrove colony survives, the mitigating effects of tsunamis may not be realized unless the forest is sufficiently wide [9].

The development of new ecological technologies is particularly

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Fig. 1. **(a)** Withered mangrove plantations (Chonburi, Thailand). **(b)** Uprooted mangroves due to the 2018 tsunami (Sulawesi, Indonesia). **(c)** Successful plantation, but a rubble dike hinders the expansion of the mangrove forest (Chonburi, Thailand) [All the photos were taken by the author].

important for protecting densely populated coasts. However, the implementation of mangrove plantations is difficult in anthropogenic environments. Coastal development leads to the loss of coral reefs, coastal vegetation, dunes, and storm ridges. The topography often exhibits an abrupt change due to land reclamation, sea dike construction, breakwater, and dredging work. Upright sea dikes reflect waves in the form of standing waves that cause strong turbulence in front of the wall, resulting in local erosion/scouring. Dredged channels may increase wave heights and significantly change the dynamics of suspended particulate matter [10–13].

Coastal development often leads to rapid subsidence due to industrialization processes such as groundwater pumping and surcharge load from high-rise buildings. For instance, Jakarta has been experiencing a very fast rate of land subsidence, reaching approximately 10 cm/year. The coastal dikes constructed in the city currently prevent flooding, but the effectiveness of this measure will disappear within the next two to three decades if subsidence persists [14,15]. Groundwater pumping including self-weight consolidation has resulted in subsidence in the Mekong Delta (Vietnam) at a rate of 2 cm/year [16]. Land subsidence is not always a slow process and is known to occur abruptly sometimes. Many small islands near Bohol, Philippines, have suddenly sank due to the earthquake in 2013 [17]. A similar situation has also been observed in Tohoku, Japan, where many ports suffered from subsidence of approximately 1 m, which was triggered by the great earthquake of 2011 [18]. As such, adaptation to relative sea level rise caused by subsidence needs to be examined to ensure the long-term performance of mangrove plantations.

In general, rehabilitation or restoration may be recommended when an ecosystem is substantially altered to the point that it can no longer renew itself [19]. However, despite the allocation of enormous funds to plant mangrove forests in recent decades in the Philippines, the survival rates of mangroves are 10–20% [20]. In the case of Thailand, the vague definition of national targets has allowed stakeholders to report "false successes" based on the land area planted, instead of the long-term survival rate of reforested mangroves [21]. Coastal management practices include five options, "protection," "accommodation," "planned retreat," "use of ecosystems," and "sacrifice" [22]. In particular, affordability and sustainability of the utilized technology is a key factor in the implementation of disaster management in developing countries.

This paper conceptualizes a new disaster countermeasure called an "adaptive mangrove hybrid platform," to advance the notion of a hybrid solution that combines engineering and ecological protections to achieve Eco-DRR, even in urban areas.

Need for structural and ecological hybrid solution

Fig. 2 illustrates the performance of different types of coastal protection, classified according to the relationship between the height and width of the system. The height of a concrete dike primarily determines the performance of the structure with respect to the mitigation of coastal

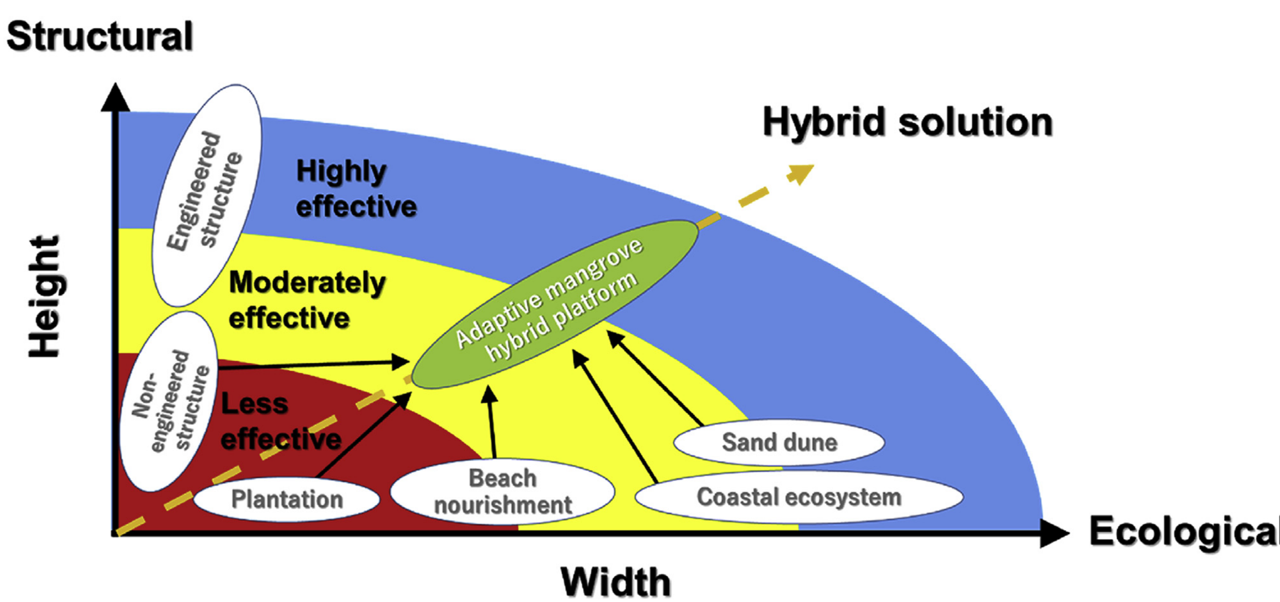

Fig. 2. Schematic diagram of the effectiveness of various coastal protections, classified according to structural height and width of the system. The adaptive mangrove hybrid platform aims to integrate several options such as non-engineered dike structure, nourishment, sand dune, and coastal ecosystem in addition to mangrove plantation. The axis of the hybrid solution is positioned between structural and ecological solutions.

hazards (i.e., the higher the wall, the greater its effectiveness). From a spatial perspective, a dike structure may be the most efficient system because it can be constructed on limited land space. However, a dike, especially a tall one, inevitably poses technical challenges such as the requirement of detailed design, good quality material, skillful engineers/workers, and strong soil foundation. For example, it appears that such an engineered structure can only be feasible in developed countries with sufficient financial resources allocated to disaster management. Dike structures are quite common in developing countries, but are often non-engineered or poorly constructed. Given the numerous limitations, the policy of coastal protections by higher and stronger dikes may not be viable in many developing countries. Instead, such countries can utilize the natural environment such as mangroves that can substantially mitigate disaster impacts.

Currently, there appears to be a significant gap between engineering (structural) and ecological solutions. Either of the two options may be considered, but a combined approach remains uncommon in the practice of disaster management. In order to combine these two solutions, an adaptive mangrove hybrid platform is proposed. In Fig. 2, this integrated solution is positioned between structural and ecological solutions, consisting of elements with moderate height and width, with the aim of disaster mitigation.

Concept of the adaptive mangrove hybrid platform

If a beach is composed of muddy sediments and has a nearly flat slope, then the gradual expansion method, which protects the plantation area assisted by temporal wood fences, may be the best solution [23,24]. This method may be effective in a natural environment or in the case of limited development. However, it will not be effective when the plantation needs to be established in a densely populated coast whose topography has been substantially altered.

Hence, the adaptive mangrove hybrid platform begins with landfill work to level the ground of the platform. Fig. 3 illustrates the transition of the adaptive mangrove hybrid platform over time. The platform needs to be carefully assessed by projecting the relative water depth to the ground surface, as formulated by Equation (1).

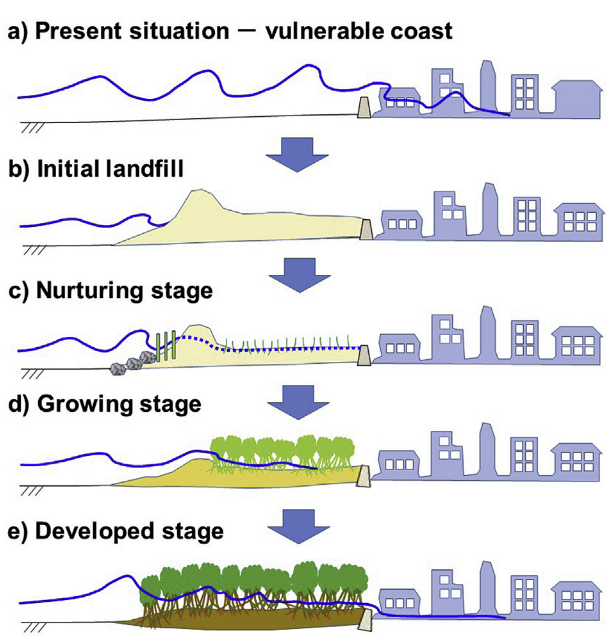

Fig. 3. Conceptual diagram of the adaptive mangrove hybrid platform over time.

$$\begin{aligned}[\text{Relative water level}] = [\text{Soil consolidation}] + [\text{Regional land subsidence}] \\ + [\text{Sea level rise}] - [\text{Sediment deposition}]\end{aligned} \tag{1}$$

If the platform is appropriately designed, the impacts of coastal hazards can be attenuated by both the platform topography and mangrove forest. Mangroves also increase coastal resilience by providing ecosystem services such as wildlife habitats, nutrient recycling, and nurseries.

a) Present situation

Developed countries may prefer to consider engineering options rather than an ecological countermeasure because they may have sufficient budgets and the design procedure has already been established. However, impoverished societies generally have very limited economic resources available for disaster management [25,26]. Some countries may be able to afford the construction of resilient coastal dike systems as high as 10 m to prevent a 5-m tsunami (Fig. 4a). A national important port may also have an advanced coastal dike, supported by expensive steel piles, with the assistance of high technology (Fig. 4b). For example, some major industrial port in Japan spent approximately 4000 USD/m^2 to elevate the dyke by 1 m with such a highly engineered solution [27]. However, such an expensive structure may not be feasible for many countries. In developing countries, there are densely populated communities in many regions that are poorly protected by thin dikes (Fig. 4c) or improvised countermeasures (Fig. 4d). Hence, the option of a tangible, affordable, and sustainable solution is of great importance in the implementation of the practice of disaster management in developing countries. Despite their budgetary limitations, many developing countries have the advantage of being able to consider an ecological solution because they are often situated in tropical and subtropical regions.

b) Initial landfill and c) nurturing stage

In general, mangrove seedlings should be grown in a location that satisfies the following conditions [28]:

- Located in the upper half of the intertidal zone
- Has low flow velocity and wave height
- Has soil with good drainage, such as sand
- Has salinity level lower than 50 ppt (5%)

Mangroves naturally grow in intertidal zones above the mean sea level [19]. Therefore, the height of the mangrove bed should be as low as the tidal elevation. However, landfill soil will inevitably sink owing to soil consolidation, regional land subsidence, and sea-level rise, among many other reasons. Salinity also affects the early development of seedlings with higher growth rates at low salinity compared with high salinity [29]. Hence, the height of the landfill should be determined by taking the initial rate of consolidation into account.

In Fig. 3, the front part of the platform acts as a breakwater to mitigate wave overtopping, with the aim of nurturing mangrove plants. For example, a stone revetment or riprap can be used for this purpose. However, the demolition of the structure will be difficult if the stone is too heavy. As a result, the expansion of a mangrove forest can be hindered, as observed in Fig. 1c. Hence, the size of the stone should be carefully determined to enable the removal of the dike at a later stage. Sustainability of the technique is important. A low-cost countermeasure, such as the use of wood piles, small stones, and portable blocks, can be used to prevent erosion of the frontal slope as short-term countermeasures. Portable and cheap materials are also preferable because they may be used for construction by local communities, which may also play a central role in community mangrove plantation and forest conservation.

Fig. 4. **(a)** A giant coastal dike in a depopulating village (Tohoku, Japan). **(b)** Construction of a highly engineered coastal dike with pile foundation in an industrial port (Tohoku, Japan). **(c)** A fragile dike protecting a densely populated village (Jakarta, Indonesia), and **(d)** A severely eroded beach, poorly protected by wood piles and sandbags (Phan Thiet, Vietnam) [All the photos were taken by the author].

d) Growing stage

It takes several years for mangrove to grow sufficiently to withstand normal waves. Therefore, a breakwater is required to sustain its function at least during the first several years after plantation. Once the plants gain sufficient strength with extended root systems, they can effectively provide protection even if the frontal part sinks owing to subsidence or erosion. Mangrove seeds are produced annually in large numbers and float to new sites for colonization [19]. Hence, the subsided front may even be beneficial to the introduction of these floating seeds, which may promote a tranquil environment, contributing to the mitigation of disaster risks. Sediment deposition is expected to remain low at this stage because the vegetation density is too low to sufficiently trap suspended matter.

e) Developed stage

Fig. 3e illustrates the final stage in which the mangroves are fully grown and provide sediments to cope with subsidence and sea-level rise. Even if a tsunami strikes, the dense mangrove vegetation can substantially reduce the energy and save lives. Equation (1) suggests that sediment deposition may be the only dependable avenue for maintaining a constant depth between the platform and water level. The rate of sediment deposition is particularly important in the promotion of vegetation growth in this final stage. Vegetation growth, in turn, contributes to the trapping of suspended sediment. Sediment accretion in mangrove forests is relatively slow, with a rate of several mm/yr [30]. Hence, insufficient elevation of the initial landfill may result in less effective protection against coastal disasters if the platform sinks excessively.

Technical challenges

For the success of the adaptive mangrove hybrid platform, the following technical issues need to be carefully investigated.

Evaluation of hydrodynamic effect

A mangrove forest on an artificial landfill is an effective tide attenuator [31]. However, the tidal amplitude cannot be reduced if the landfill's cross-shore width is narrow. A tidal damping ratio of over 50% is expected if the width exceeds 200 m (Fig. 5). Higher ratio of mangrove vegetation growth contributes to the attenuation of tidal amplitude, whereas the performance of the mangrove with lower growth ratio may be limited in reducing the tidal amplitude [31]. Tsunami flow pressure may be reduced by more than 90%, but it requires at least a 100-m wide belt with 30 trees per 100 m^2 [6]. It has been estimated that a dike-break induced flood, which could be triggered by the sudden collapse of a dike, is significantly mitigated by the construction of a landfill with a width of only 20 m, with fully grown mangroves in front of the dike [32]. The impact of the type of tsunami induced by sudden dike failure would be substantially mitigated by planting a mangrove belt in front of the dike; via two mechanisms: (1) a reduction in floodwater velocity and inundation depth and (2) a flow-smoothing effect, which reduces strong

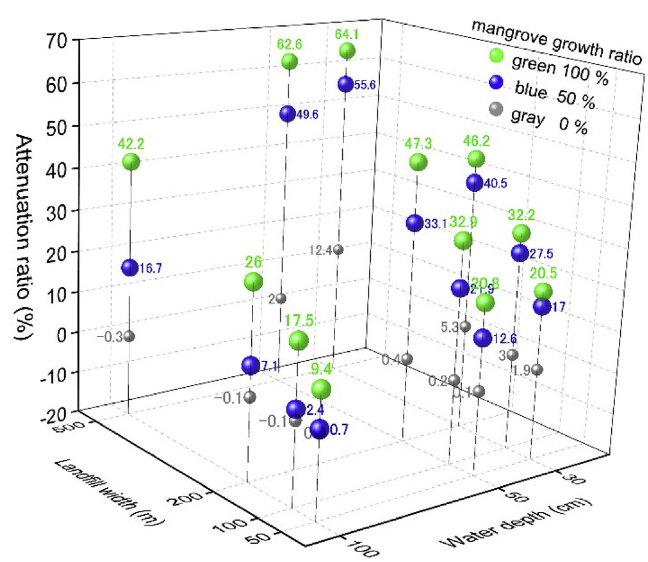

Fig. 5. Calculated tidal damping ratio according to plant growth ratio, landfill's cross-shore width, and water depth [31].

turbulence. In this way, the reduction in flow velocity and wave amplitude is highly dependent on the characteristics of the waves (particularly wave period) as well as the dimensions of the system and mangrove characteristics, such as the density, height, and diameter of the plants.

Prediction of land subsidence/soil consolidation

The platform will immediately start sinking owing to soil consolidation and regional land subsidence. Fig. 6 illustrates three typical scenarios: Scenario 2 shows the case where the platform is maintained with relative sea-level rise by achieving an equilibrium state, while Scenario 3 represents the case where the platform is excessively submerged. In Scenario 3, mangroves may no longer inhabit the area because strong waves and tidal flows propagate over the bed, causing less sediment trapping and no remarkable effect on disaster mitigation. In contrast, Scenario 1 shows another case where the platform is higher than the water level during its lifetime. This situation could occur when the initial platform was set too high compared with the rate of consolidation and sea-level rise. Although Scenario 1 may not be classified as an ecological solution, it still works as an artificial sand dune. Hence, reliable prediction of the evolution of the platform over time is important in designing the initial elevation of the landfill to achieve the successful case of Scenario 2.

Factors that determine mangrove growth and sediment deposition

To transform a landfill into a mangrove platform, various conditions must be met. Among the many factors, the promotion of sedimentation is critical to the success of the platform. Once the elevation of the platform is such that plant development is feasible, the surface is colonized by vegetation, which in turn promotes sediment trapping. The failure of mangrove rehabilitation is often attributed to lower structural complexity than that of a natural forest [19]. For example, most of the rehabilitation programs in the Philippines used a single mangrove species such as *Rhizophora* [20]. Different species require different nutrients, elevations, saline conditions, and tidal conditions [33,34].

Soil type

Soil properties largely differ among mangrove forests in terms of pH, salinity, bulk density, cation exchange capacity, nutrients, carbon, and organic matter content of mangrove soils, resulting in difference in vegetation, species composition and structure of mangrove forests [35]. In many mangrove forests, the soil respiration rate is low because of anaerobic soil conditions. These trends in biomass allocation, net primary production, and soil respiration will result in high net ecosystem production [36]. Fig. 7 shows that different soil conditions will alter the speed of growth of mangrove seeds even under the same controlled environment. In this example, plants in the small pot with native soil seems to grow faster and were healthier than those in non-native soils. Therefore, soil suitable for mangrove culture should be carefully examined.

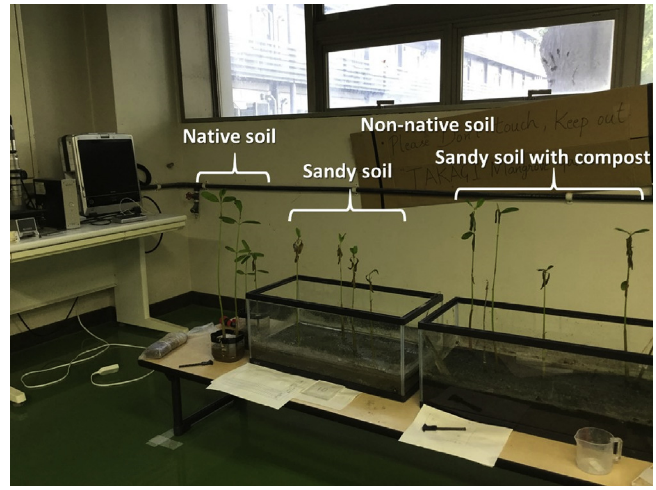

Fig. 7. Mangrove growth about five months after planting seeds (*Kandelia obovate*) under a controlled environment in the author's experimental laboratory (Tokyo, Japan). In addition to the native soil, two non-native soils (sandy soil with/without compost) were tested to observe any difference in growth rate.

Conclusions

The affordability and sustainability of the utilized technology are key factors in the implementation of disaster management in developing countries. Although a 10-m coastal dike is an option in some developed countries in response to future tsunamis, this is often not a viable solution in developing countries owing to financial limitations. Instead, communities in tropical and subtropical regions have the advantage of

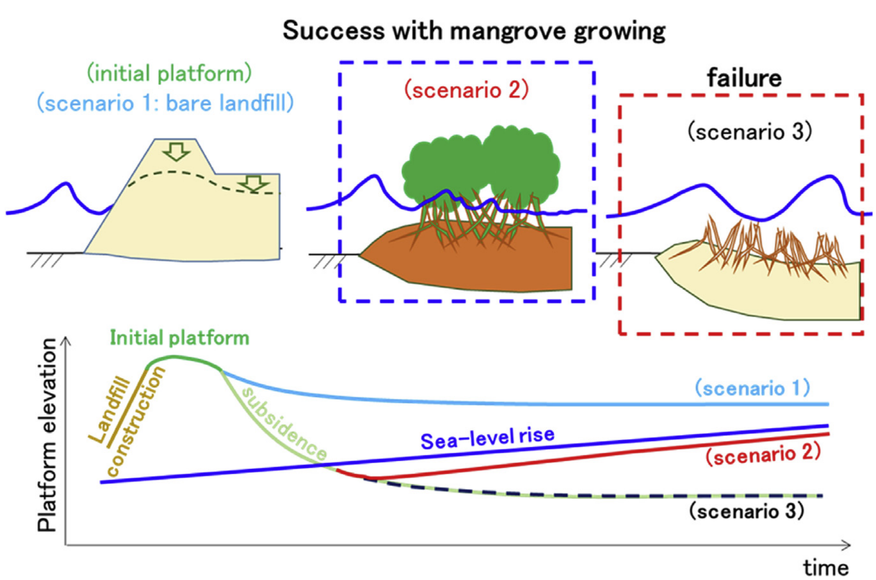

Fig. 6. Adaptive mangrove hybrid platforms and their transitions over time.

considering an ecological solution based on ecosystems. In particular, mangrove forests are expected to act as natural infrastructural buffers against coastal hazards. Unlike untouched natural environments, however, mangroves cannot grow along urban coasts where the water is too deep. Hence, the author proposed “the adaptive mangrove hybrid platform,” which is a hybrid of engineering and ecological solutions. The platform will inevitably sink owing to relative sea-level rise. Therefore, the initial geometry of the landfill needs to be appropriately designed to achieve an equilibrium state, such that the ground surface is adaptively balanced with the water level. The main challenges as well as the advantages of this technology were discussed to conceptualize this hybrid countermeasure for further study.

Author contributions section

This paper was solely written by one author, Hiroshi Takagi.

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Erratum regarding missing Declaration of Competing Interest statements in previously published articles

Declaration of Competing Interest statements were not included in the published version of the following articles that appeared in previous volumes of *Results in Engineering*.

The appropriate Declaration/Competing Interest statements, provided by the Authors, are included below.

" 'Adapted Mangrove on Hybrid Platform' – coupling of ecological and engineering principles against coastal hazards" Results in Engineering, 4(2019), https://doi.org/10.1016/j.rineng.2019.100067.

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"Probabilistic modeling of excavation-induced damage depth around rock-excavated tunnels" Results in Engineering, 5(2020), https://doi.org/10.1016/j.rineng.2019.100075.

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"Multi-channel modelling approach for particulate filters" Results in Engineering, 5(2020), https://doi.org/10.1016/j.rineng.2019.100077.

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