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Application of bamboo in mangrove rehabilitation projects

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Mangroves have proved to be an asset to coastlines owing to their various advantages in terms of coastal protection and stability. Along tropical coastlines, as mangrove tracts recede and threats of coastal erosion mount, mangrove rehabilitation projects are being seriously contemplated. The design of such projects, however, is in an incipient phase, and several technical and economic challenges are to be faced. The plantation and growth of mangroves requires a protected coastal environment with proper drainage of the soil substratum. Hence, in a sample design undertaken for a mangrove rejuvenation project along the eastern coast of Mumbai (India), various layouts have been studied for a protective coastal structure and drainage system. One such design uses bamboo pile walls in creating shielded compartments (with multiple compartmental layouts) for mangrove growth, along with bamboo drains. The bamboo-based structure was found to be environmentally and economically advantageous over other designs such as sand dykes, which are many times more expensive. Moreover, employing natural material such as bamboo helps the structure integrate with the developing mangrove habitat, allaying concerns about dismantling the structure after mangrove growth. A cost-minimising and eco-friendly bamboo structure such as this therefore promises to pave the way for large ecological projects in the future, spanning over 1000 ha.

1. Introduction

Rich mangrove communities are found in tropical and sub-tropical coasts that experience high rainfall and summer temperatures. The presence of mangrove ecosystems has been shown to have a positive impact on coastal stability, water quality, flora and fauna, and the aesthetic of the coastal landscape. It is thus important to plant and protect mangrove habitats along coasts, especially when existing mangrove reserves are facing increasing threat due to global warming and urbanisation.

There is a host of literature on mangrove plantations along coastal environments, particularly concerning large-scale rehabilitation projects in the Philippines (Primavera and Esteban, 2008) and Malaysia (Othman, 1994). A major replanting project is also to be undertaken in Sri Lanka (Kinver, 2015). However, conceptualisation of the design and layout of structures that could protect mangrove plantations during growth has not been found in the literature, which is the aim of this paper.

The plantation and subsequent protection of mangroves requires that a suitable soil substratum be made available for the growth of mangroves coupled with the building of a confining structure to protect the mangroves once planted. While the

need for appropriate soil warrants a detailed study of the quality and composition of dredged mud in the vicinity of a project, this paper will focus on the other major requirement – that of designing the layout and make-up of the confining structure. It must be remembered, however, that the availability of dredged mud will dictate various aspects of design, such as the proposed geography, project layout and bottom support for the confining structures.

Alternatives in terms of arrangement and design material have been considered for these confining structures, and the utility of bamboo in such designs has been found to be helpful for the dual purpose of protection from the sea and drainage. Moreover, the idea of using a natural material such as bamboo in order to protect a mangrove habitat not only reduces the cost of human intervention but also makes the design environmentally more acceptable.

In order to assess a sample design and the feasibility of its application, it was necessary to locate it in a geographical region where such a project could be envisaged in the future. However, it should be noted that although the broader framework of the design of a mangrove rehabilitation project may remain the same across geographies, specifics such as the

mangrove species and weather conditions may differ from case to case.

2. Description of the study site (Mumbai)

Identification of a site for implementing such a project requires consideration of

- the availability of soil types suitable for mangrove growth
- location in a tropical or subtropical climatic regime along a shoreline, particularly intertidal environments
- the presence of a harbour or navigational channel in close proximity to the site for availability of dredged mud supplies
- the evidence of pre-existing mangrove forests in the area to prove conducive conditions
- the commercial landscape of adjoining regions and the potential environmental benefits.

A site that accommodates all of these conditions to some extent was identified within the metropolitan borders of the Indian city of Mumbai.

In the 1990s, an area of around 37 km² of mangrove existed in Mumbai, mostly along its western suburbs and Thane Creek. Some sparsely covered patches of mangrove are also found in the south. However, since then, mangroves along the coast of Mumbai have faced challenges from various anthropogenic activities (Deshpande, 2013).

The most commonly occurring species of mangrove in Mumbai is *Avicennia marina*, which accounts for almost 60% of species diversity (SPGMEC, 2015). The characteristic feature of this species is its tolerance to high salinity, but it also tolerates pollution from heavy metals such as lead, mercury and chromium (Kaujalgi, 2010).

Out of the six administrative zones delineated by the Mumbai Metropolitan Region Development Authority, only three hold large mangrove stands and the potential for additional mangrove restoration. Kaujalgi (2010) conducted research to determine which areas out of the six zones were more suitable for mangrove restoration. However, bearing in mind the considerations listed at the beginning of this section, it was considered that the coast covering zones V and VI along the eastern coast of Mumbai adjoining Thane Creek (see Figure 1), which is closely accessible from Mumbai port, would be the ideal site for this study.

Additionally, for such a project, the seaward reach needs to be demarcated. The minimum mangrove width for complete wave height reduction was found to be 500 m by applying the formula proposed by Quynh (2010) (see Figure 2), assuming 80% mangrove coverage and 1000 trees per hectare. In Figure 2, K_t is the reduction in the wave height H_s , given by H_s at the location divided by H_s at the outer edge of the

Mangrove belt. This offshore extent of about 500 m can be further justified for two reasons. Firstly, as observed from available bathymetry charts of Thane Creek (Vijay *et al.*, 2014), the depth of water does not change drastically over this distance and this is essential since mangrove plantations require a surface with reasonably low gradient. The second reason is the availability of dredged fines. Maintenance dredging in Mumbai port totals 7 million m³ in the main channel once every 4 years and 2 million m³ in the approach and other cross-channels every year (Jayappa and Narayana, 2009). A mangrove project of dimensions 27 km × 500 m, with a minimum layer height of 50 cm for the first roots (which grow up to 30–35 cm), means a requirement for dredged material of up to 7 million m³, which is the roughly the amount available from one cycle of maintenance dredging. Also, it is important to note that not all the dredged material is silt and clay; it also contains a small proportion of sand.

Regarding climatic conditions at the site, the western side of Thane Creek (facing the study site) generally has ebb-dominated flow whereas the eastern side experiences slightly flood-dominated currents. The northern portion extending from Pir Pau experiences low residual currents (<0.05 m/s), whereas values of 0.25 m/s are found in the southern part (Naidu and Sarma, 2001).

In sheltered short basins such as Thane Creek, locally generated waves are most important in determining design criteria. The driver for these local waves is the wind at the location and therefore local wave estimation has to begin with an analysis of wind data. The BMT ARGOSS database (2015) was used for this purpose. When deciding which sections of the data would be relevant to the design, the two important factors considered were the direction and seasonality of wind. Firstly, those directions of wind unlikely to produce any waves towards the region of interest were discarded. Therefore, wind data falling within this zone, which is roughly directed from the north to the southwest, had to be eliminated. Also, given the location of Mumbai within the southwest monsoon geographical climatic zone, one also needs to bear in mind that the monsoon season extending from July to September is a season of frequent and torrential rains accompanied by strong winds and swell-wave action from southwest, which could potentially affect the wave climate within Thane Creek.

It was found that there is a roughly one in ten year chance that a wave as high as 1.9 m may be caused by the wind in critical zones. Although a relatively low probability, this was used as a limiting height for the design of the containing structure. Given that there could be errors introduced in the dimensions of the structure due to issues relating to subsoil settlement, a conservative limiting wave height makes added sense. Also, it should be noted that the probabilities of exceedance of this wave height are for a 50-year duration and not for longer periods as is the case with many designs, because



Figure 1. Broad outline of potential coastline selected for the case study, near the major docks and harbours under the Mumbai Port Trust (indicated by the rectangular box). Map data ©2016 Google

the required service of the structure is for a short duration of 1–2 years.

3. Bamboo piles as confining structures

Having identified a suitable site and extent for the project, the next stage was to conceptualise a design for the retaining structure. It is important to highlight here that the proposed structure could be built into a previously defined site in the form of different layouts, which are discussed in Section 5.

Since retaining/confining structures in mangrove rejuvenation projects are intended to be temporary and not for long-term protection of the coast, it makes little sense to have a hard structure built for confinement during plantation and growth. Expensive options such as building a seawall or using concrete kerbs were thus ruled out at the outset.

Two options emerged for a relatively temporary structure – a sand dyke or bamboo piles. Designs for the dyke were created through conventional design practices, as defined in the EurOTop manual (EurOTop, 2007). Although designs of split-bamboo pile walls have not been frequently tried and tested in coastal environments, bamboo as a construction material has been used extensively in tropical areas. The design of the dykes was carried out for the same boundary conditions as those of the bamboo piles, but the focus of this paper will be primarily on bamboo piles. However, the dyke designs were used in the cost comparisons to highlight the advantages of using bamboo over sand structures.

Primarily, in the bamboo-based design, a fence consisting of bamboo piles was considered for the retaining structure. Bamboo poles have been used for protection from waves in

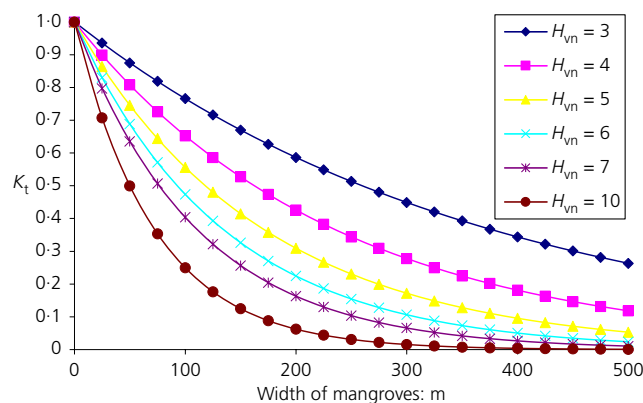


Figure 2. Design graphs for the width of mangroves using the formula of Quynh (2010) (Verhagen and Loi, 2012). H_{vn} , the average total height of trees in the forest (m); and K_t , the reduction of wave height in mangrove forest



Figure 3. Bamboos with reed filling in the gaps being used as wave screens along a T-groyne in Vietnam (photo by H. J. Verhagen)

various cases, such as walls in aquaculture farms or as groynes. A T-groyne with bamboo wave screens for a project in Vietnam is shown in Figure 3. The protection was made as a double bamboo row with reeds in between. The bamboo pile wall proposed for mangrove rehabilitation would look similar, with bamboo culms and reed panels in the gaps. The piles will have to be structured as aligned together, resembling a wall. An arrangement consisting of vertical halved culms, for example, could be considered.

A sample design of such a wall is shown in Figure 4. When the design of such a structure is being considered, the main aspects that need to be considered are the height of the piles and the bottom support of such piles. The height of the pile has similar deterministic conditions as those mentioned for the height of the dyke. A typical piled wall in a wave environment will experience several loading conditions as it is being built and during the various construction stages. The significant forces are

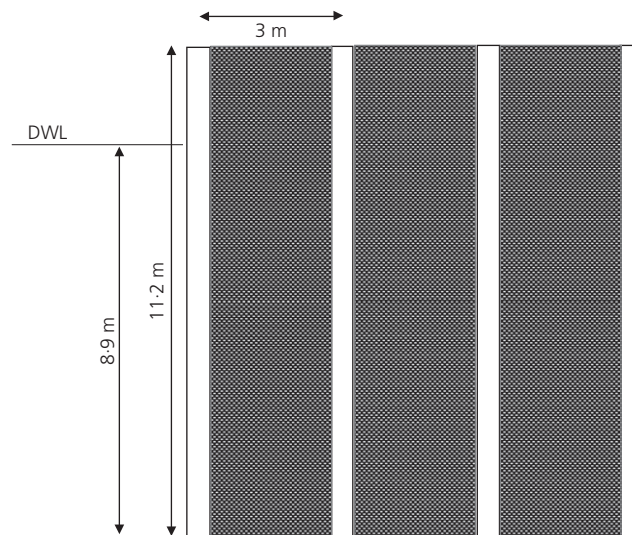


Figure 4. Design of bamboo piles with panels in between

hydrostatic pressure, forces due to soil loads, water current forces, wave forces and accidental loads. Accidental forces or storm forces were not considered for this design, bearing in mind the period and purpose of the intended structure. The design of the split-bamboo pile walls in this case was carried out based on the overtopping found for small vertical walls over dykes (EurOtop, 2007), which was found to be 11.2 m (see appendix A in the Supplementary Material). This does not indicate a precise value, but is an approximation obtained through design. It should also be noted that tolerance of water by mangroves as well as accommodation for subsoil settlement may make up for any deviations in the design height.

Apart from the height, other pile dimensions were estimated from previous examples. Another important factor in these dimensions is the spacings between piles. Relatively large spacings need to have some kind of panelling to complete the 'piled wall', which will be discussed later in this section. Design practices in other applications suggest that the spacings between piles must be about ten times the diameter of the pile (Fang, 1997). The most common type of bamboo found in the areas close to the project (*Bambusa balcooa*) is about 130–150 mm in diameter. An approximately 15 cm diameter implies that the spacing between piles should be about 1.5 m.

The bamboo pile walls are considered to consist of framing members, which could be half culms (see Figure 5 for an indicative diagram of framing). An infill material is required to fill the gaps between these culms. The infill material is crucial in this case because it is not supposed to allow clay to pass through, which will be required within the confinement as a substratum for the mangroves to grow. Most of the information for such infill material was obtained from a report produced by the International Network of Bamboo and Rattan (Janssen, 2000).

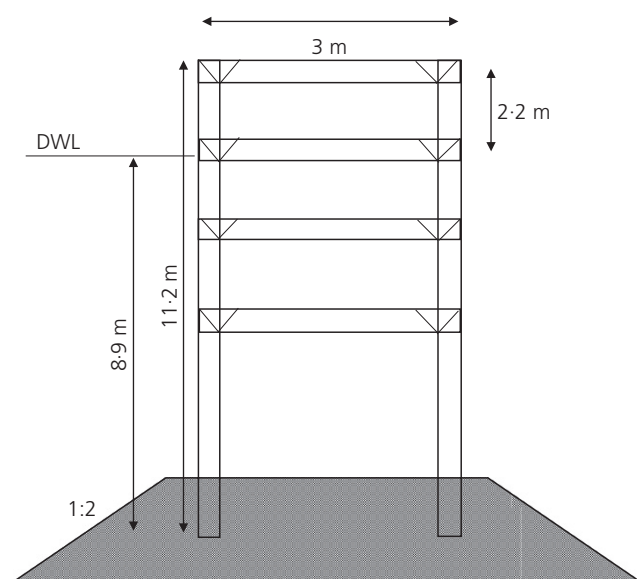


Figure 5. Piled bamboo wall framing with horizontal pressure bars tied with woven bamboo strips

The infill panels could be made of whole or halved vertical or horizontal bamboo culms, which could be driven directly into the ground. The vertical culms could also be anchored between the horizontal ones, acting as bottom support. Otherwise, mats of halved bamboo culms could also be tied using bamboo battens. A vertical arrangement of such half-culms is good for shear resistance. The choice of using vertical half culms of bamboo without plastering seems to be optimal, despite these not being structurally sound as bamboo panels. However, considering that the target period for such a structure is quite low (less than 2 years), this seems to be less of a worry. What is more important is the reasonable mud-tightness provided by bamboo culms and the reduced cost as no weaving or plastering operations are involved.

3.1 Pile support

Technically, for bottom support for the piles, an array of options could be considered, including sand mounds, boulders and bamboo mats. The advantages and disadvantages of each are now discussed briefly.

3.1.1 Sand mounds

Sand mounds would be below the design water level (DWL) and would not be subject to major wave loads. However, considering the conditions in Mumbai, strong tidal currents to and from the shore could be expected (see appendix B in the Supplementary Material). The toe of such a sand mound would also require protection against scour under high wave conditions.

3.1.2 Boulders

Appropriately sized boulders can provide adequate defence against currents for a short period of time. However, one of the problems with using boulders is that clay could escape from under the bamboo piles through gaps in the boulders, making this choice less desirable for bottom support. Also, rocky environments are not best suited for mangrove growth. Mangroves can grow on sandy or rocky coasts or on carbonate or reef sediments but tend not to reach the height, density or extent of mangroves growing on marine clay (Joyce, 2006).

3.1.3 Bamboo mats

Bamboo mats are made by weaving together thin strips of bamboo, which can vary in size from 20 mm × 2 mm to 2 mm × 1 mm. It is evident that, for the expected protection against percolation of mud (with grains having diameters smaller than 1 mm), thin dimensioned strips cannot be used as the gaps between these strips could be of the order of magnitude of the particle dimension, thus creating too many gaps for clay to pass through. Thicker mattresses could be held in place by weighty bamboo strips or timber battens, making this protection naturally integrated with the mangroves.

In practical terms, for the design of bottom support, some hints are available from the design of fish farms that use bamboo piles as retaining structures (Cruz, 1983). Some designs suggest that boulders are laid between the piling to about 20 cm thickness to form a floor. A gravel layer of 5 cm thickness is spread on top of the boulders, and then compacted (see Figure 6). The exposed ends of the piles should be level with the surface of the gravel layer. A similar support consisting of boulders or other large supporting rocks available from

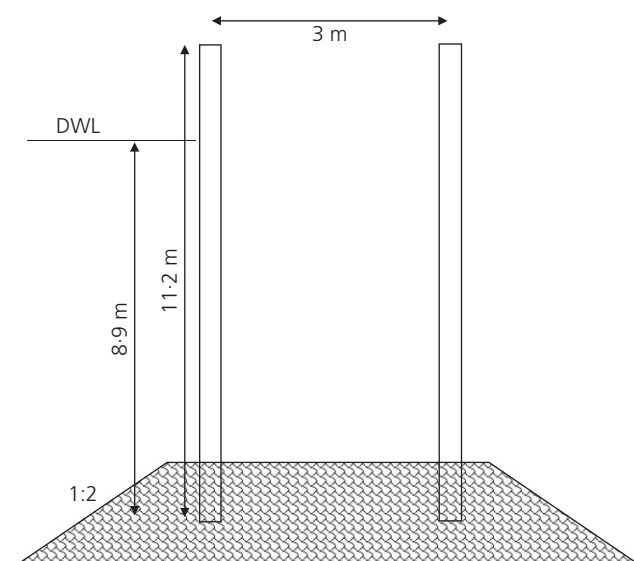


Figure 6. Piled bamboo wall supported by boulders

the Western Ghats could be made use of for supporting such a structure along the eastern coast of Mumbai.

4 Bamboo as drainage material

Stulz and Mukerji (1988) reported that split-bamboo piles have been developed to improve the bearing capacity of soft compressible soils and to reduce settlements for various types of construction (buildings, roads, etc.). An advantage of using this method for the drainage of water from mud is that it can be well integrated with the bamboo pile wall design considered for the confining structure.

In fact, the bamboo piles used for confining structures could be replicated for the purpose of drainage. However, the draining properties of such piles and the infill material need to be given special consideration in this case. In this section, the infill material does not refer to the panels or members between piles but the nature of the material (drainage medium) that will be placed inside the bamboo culms. Thus, in this case, the ‘drain pipe’ will be the bamboo pile itself and it will function as the surrounding support for the drainage media. Additionally, bamboo culms can have extremely minute holes drilled into them to allow water to seep through.

The next consideration is the type of drainage media to be used. Two alternative materials could be used for such purposes – coconut fibre or jute threading – both of which are quite easily available in the location of the proposed project. Stulz and Mukerji (1988) reported that hollow bamboo culms can be filled with loosely wound coconut coir and jute thread wrapped in jute fabric; holes in the culm permit water in the soil to trickle in, thus drying out the soil and improving its load-bearing capacity. However, if materials such as coconut coir and jute are being considered, the diameter of such strands needs to be ascertained. For soft soils with a top layer of about 2 m thickness, 6 mm diameter coir could be used in the split-bamboo piles. One of the reasons for this would be their ability to trap particles of even larger size (up to 2 mm) while allowing water to pass, thus functioning as a filter. Apart from the size of the coir, other factors that need to be considered are coir properties, applicability and availability.

5. Layouts for placement

The design methodology for the planned reuse of dredged mud in the basin for the mangrove plantation also has to consider the placement and layout of mud, as this will determine the overall length of the confining structure and the corresponding material requirements. The layout will determine two important aspects of the project – the spatial placement and the temporal procedure of that placement. Mangroves are confined to the upper intertidal zones of sheltered sedimentary coasts and estuaries (Balke, 2013). Mangroves’ niche between land and sea has led to unique methods of reproduction. Seed pods germinate while on the tree, so they are ready to take root when

they drop. The ‘niche’ zone to which mangroves are confined puts limitations on the spatial extent of the envisaged project. The placement of mud is restricted mainly in the intertidal zones, which helps to establish the onshore and offshore extents of the placement. The alongshore extent was previously delimited during identification of the study site, based on the conduciveness of the certain part of the shoreline for the mangrove plantation.

As discussed earlier, the design will comprise the placement of mud accompanied by a suitable filtering (permeable) structure offshore. Permeable structures made of local materials such as bamboo, twigs or other brushwood could be placed in front of the coastline. These structures let seawater pass through, thus breaking the waves rather than reflecting them. As a result, the waves lose height and sediment is trapped at or near the coast. These devices imitate nature – mimicking the structure of a natural mangrove root system (Tonneijck and van Eijk, 2015). This could be a good starting point to consider for the functionality of the confining structure. Also, until the mangrove seeds germinate and the mangrove plants actually take root, it will be permeable structures such as these that will keep the placed dredged material from flowing away offshore.

The layout of the confining structure can take various forms, ranging between three major patterns – compartmentalised placement through containment paddocks, placement with alongshore structures and offshore structures with vertical drains.

5.1 Compartmental layout

One of the procedural designs for laying the mud is the pattern of compartmentalised placement shown in Figure 7. This method basically would firstly mean dividing up the intended coverage area into suitable sections. This is followed by setting

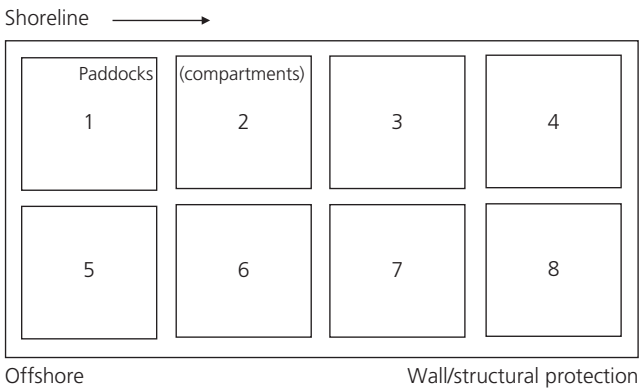


Figure 7. Placement of mud into compartments or ‘paddocks’ (numbered 1 to 8). The sketch indicates the shoreline and offshore extent. Note: the width from the shoreline to farthest offshore extent is 500 m

up mud-filters or permeable boundaries along the borders of these sections. Sequential placement of the dredged mud can then be carried out in each compartment depending on accessibility and output capacity of that particular section. Following this, the mud has to be left to undergo self-weight consolidation while the efficacy of the filters in draining out water is monitored.

At the outset, one advantage of this method is that section-by-section placement may help in obtaining proper feedback on whether the placement method is indeed working in one compartment. Equipped with feedback and any requisite improvements, the next compartment can be laid more effectively. One example of such a layout has been successfully carried out in Australia (not for the purposes of mangrove rejuvenation): dredged mud was placed into containment paddocks in a slurry form, dewatered and allowed to undergo self-weight consolidation (Ganesalingam *et al.*, 2011). Another benefit of a compartment-based placement, especially in a busy city like Mumbai, is that it may allow time for alternative projects or utilities in other charted compartments to relocate.

5.2 Alongshore parallel layout

Another alternative worth considering could be step-wise placement of mud in alongshore strips gradually moving offshore to cover the entire intertidal zone (Figure 8). An overview of the directions and magnitudes of currents along the shore may also be significant in such a placement.

The need for a confining structure may persist. It is, nevertheless, important to note that the confining structure in this case will have to be lengthier than that required in the compartmentalised layout. However, as the mangrove swamp gradually takes root and progresses, it will provide reasonable stability in the landward zones. Additionally, the placement could be

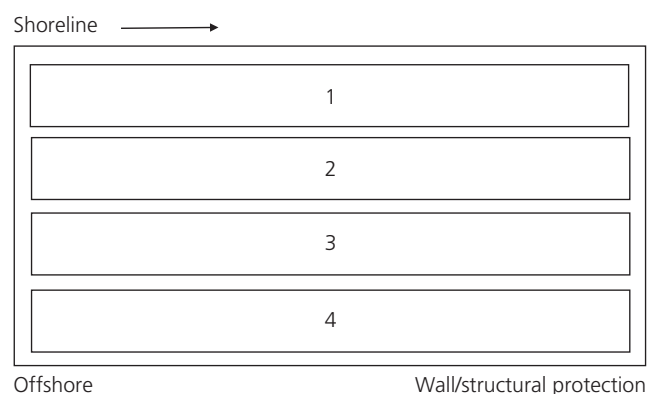


Figure 8. Simultaneous placement of mud on an alongshore stretch (each stretch numbered 1 to 5) with gradual movement offshore. The offshore side is to be contained by a permeable structure

commenced at favourable low-tide intervals wherein the along-shore water levels will be low.

This method involves planning of the stages and the building of a permeable structure that could be effectively moved or a filter that could be relocated further offshore over time, and this may present an important logistic difficulty. Additionally, some delay may be introduced at every stage based on the wait induced by the mangrove germination period.

5.3 Layout with vertical drains

The third alternative is a layer-by-layer vertical placement of the mud accompanied by the installation of vertical drains made of suitable material (Figure 9). Such a placement would lead to a gradual increase in mud levels, akin to the gradual evolution of a natural mud flat. There are studies that suggest that prefabricated vertical drains and surcharge have often been used to accelerate the consolidation process (Ganesalingam *et al.*, 2012).

One possible positive of this method is simultaneous placement along the entire area without major time delays. It also may lead to quicker drainage due to the presence of vertical drains, although the efficiency will depend greatly on the number, construction material and arrangement of the drains. Furthermore, it is extremely important that the drains are integrated with nature since they will stay within the built mud even after the mangroves take root.

Finding suitable materials and arrangements for vertical drainage may be a challenge, which makes it important to look at the availability of local materials such as bamboo or wick. In addition, the stability of the mud will have to be continuously monitored. The role of geotextiles or rock mattresses along the bed in combination with the vertical drains may be significant for the overall stability of the mud. Also, the simultaneous placement procedure implies that all existing activities in and

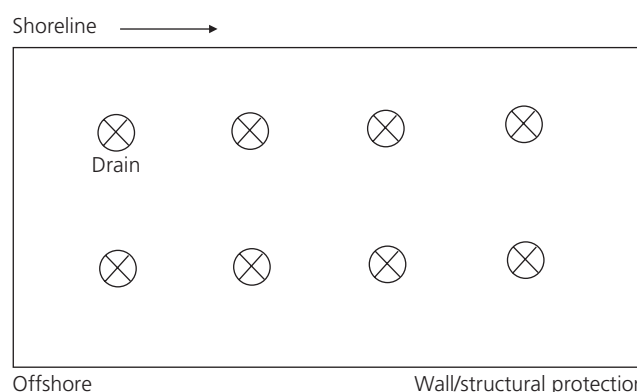


Figure 9. Vertical placement of mud with the presence of vertical drains (crosses indicate drains going into the page in this diagram)

around the zone may have to be suspended during the period of building the mudflat.

6. Some issues with bamboo

While it has been demonstrated that bamboo could be a potential building material in coastal environments, there are areas of concern that must be considered. Untreated bamboo constructions are usually supposed to survive a lifespan of 1–3 years when in contact with soil and atmosphere, even in humid conditions (Janssen, 2000). This is favourable since the purpose of the intended structure is within this proposed lifespan. However, one must bear in mind that repeated spells of wetting and drying would weaken the structure. Considering the predominantly tidal environment in Mumbai, this could be a critical problem and may hasten the process of failure. Another area of concern is infestation of the bamboos by insects that can slowly destroy the strength of the structure. However, according to Janssen (2000), physical methods such as soaking in water, clump curing and seasoning could help make bamboo more resilient to infestation by organisms.

7. Costs

A comparison of costs (Table 1) between the bamboo pile wall, as represented in Figure 4, and an optimal sand dyke design, as represented in Figure 10, was carried out in order to determine the most cost-efficient structure (see appendix C in the Supplementary Material for detailed tables). It is quite evident Table 1 that the bamboo pile walls are far more efficient in terms of net cost in comparison to the sand dyke.

Table 1. Costs of sand dykes and bamboo pile walls for three different layouts

	Cost: billion INR	
	Bamboo pile wall	Sand dyke
Compartmental placement	8.5	1000
Alongshore placement	6.7	850
Vertical placement	5.5	500

Clearly, sand dykes have a high sand requirement, which would often have to be transported to Mumbai from long distances. In fact, the net price for the bamboo pile walls is almost two orders less than the net price for the sand dyke. This is because the dyke requires a higher footprint in terms of base area and its expansion in the lateral direction whereas bamboo piles are thinner structures spaced over distances with a lower footprint in terms of ground area.

In most cases, bamboo pile walls would be the preferred design although an alternative sand dyke design may be considered in areas where sand is cheaply and abundantly available and there are no space constraints. When considering the arrangement, making compartments yields an increased cost.

In most projects of medium to large scale (tens of kilometres of coastline), the retaining structures will be the determinants in terms of costs. The drainage mechanism costs are insignificant in comparison. The cost calculations also indicate that in places where natural construction materials such as bamboo and fill materials such as coconut or jute are available, these will yield the design with the least net costs, considerably lower in comparison to sand-based alternatives. When combined in an effective manner, certain compartmental patterns can lead to acceptable costs, with only 10–15% higher investments in compared with non-compartmentalised designs.

The costs clearly indicate that the retaining structure must be one that uses split-bamboo pile walls. The two-fold advantage of using these is the fact that, firstly, they will occupy a smaller space on the ground and therefore allow a larger area for the plantation of mangroves and, secondly, they are much cheaper than constructing dykes. In addition, the construction schedule of bamboo pile walls can be carried out in much more eased out process than that of dykes where operations have to be carried out simultaneously for different compartments if the project is to be completed within one season.

The only downside of the use of split-bamboo piles is that it leaves more room for the area to be drained and hence a

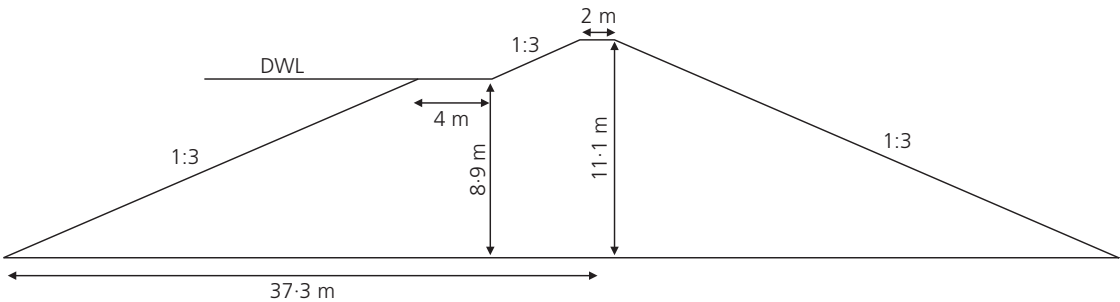


Figure 10. Sand dyke design found to be most optimal in terms of space and volume requirements

higher number of drains will have to be installed. However, given the incremental cost of these drains and their small number in comparison with the total number of bamboo piles to be installed for the wall, the increased drainage requirement is not a major concern in the selection.

When it comes to drainage, the use of bamboo drains seems to be the most efficient and cost-effective option available. The cost of bamboo as a cover material is ten times less than the cost of any other non-woven geotextile and hence this would be a huge saving. Also, as has been repeatedly emphasised, the use of natural materials such as bamboo and jute means that they will be easily integrated with the mangrove environment and will require no removal after the mangroves are grown.

8. Conclusion

This case study of Mumbai demonstrates that a successful mangrove replantation project would entail an applicable design procedure coupled with pragmatic use of natural materials. A bamboo pile wall together with bamboo drains, when arranged in a suitable layout along a stretch of Mumbai's eastern coast, could make it feasible to accomplish the revival of mangrove swamps of about 15 km² in area at considerably low cost. Although the design awaits translation into reality, this practical study of an actual geographical location has provided valuable insight into the boundary conditions and outcomes of such a design.

Moreover, this case study opens up possibilities for environmental rejuvenation in eco-fragile polluted cities in developing tropical countries by leveraging one of the widely available structural materials – bamboo. Mangrove rehabilitation projects in such countries will become possible only if they are deemed technically, economically and environmentally viable. Importantly, in this context, the use of bamboo as a building material is significant because it provides for a simple, practicable design with low costs and good integration with the natural environment.

REFERENCES

- Balke T (2013) *Establishment of Biogeomorphic Ecosystems: A Study on Mangrove and Salt Marsh Pioneer Vegetation*. Thesis, Radboud University, Nijmegen, the Netherlands.
- BMT ARGOSS database (2015) <http://www.bmtargoss.com/> (accessed 05/01/2017).
- Cruz CD (1983) Construction of a fish farm. In *Fishpond Engineering: A Technical Manual for Small-and Medium-Scale Coastal Fish Farms in Southeast Asia* (Rabanal HR and Soesanto V (eds)). FAO, Manila, Philippines. See <http://www.fao.org/docrep/field/003/E7171E/E7171E00.htm#TOC> (accessed 05/01/2017).
- Deshpande V (2013) Oil leak destroys mangroves on Mumbai coast. *The Hindu*, 8 November.
- EurOTop (2007) *Wave Overtopping of Sea Defences and Related Structures: Assessment Manual, Die Küste*. EurOTop.
- Fang HY (1997) *Introduction to Environmental Geotechnology*. CRC Press, Boca Raton, FL, USA.
- Ganesalingam D, Arulrajah A, Ameratunga J, Boyle PJ and Sivakugan N (2011) Geotechnical properties of reconstituted dredged mud. *Proceedings of Pan-Am CGS Geotechnical Conference, Toronto, ON, Canada*. Canadian Geotechnical Society, Toronto, ON, Canada, pp. 1–7.
- Ganesalingam D, Ameratunga J, Schweitzer G, Boyle P and Sivakugan N (2012) Anisotropy in the permeability and consolidation characteristics of dredged mud. *Proceedings of ANZ Conference. Australian Geomechanical Society and New Zealand Geotechnical Society*, Melbourne, Australia, pp. 752–757.
- Janssen JJA (2000) *Designing and Building with Bamboo*. International Network of Bamboo and Rattan, Eindhoven, the Netherlands.
- Jayappa KS and Narayana AC (2009) *Coastal Environments: Problems and Perspectives*. I.K. International, New Delhi, India.
- Joyce K (2006) *Wetland Management Profile*. Ecosystem Conservation Branch, EPA, Queensland, Australia.
- Kaujalgi SG (2010) *Introducing Mangrove Mitigation to the Urban Development in Mumbai*. Virginia Polytechnic Institute and State University, Blacksburg, VA, USA.
- Kinver M (2015) Sri Lanka first nation to protect all mangrove forests. *BBC News*, 12 May.
- Naidu VS and Sarma RV (2001) Numerical modeling of tide-induced currents in Thane Creek, west coast of India. *Journal of Waterway, Port, Coastal, and Ocean Engineering* **127**(4): 241–244.
- Othman MA (1994) Value of mangroves in coastal protection. *Hydrobiologia* **285**(1–3): 277–282.
- Primavera JH and Esteban JMA (2008) A review of mangrove rehabilitation in the Philippines: successes, failures and future prospects. *Wetlands Ecology and Management* **16**(5): 345–358.
- Quynh VV (2010) Effects of wave break, sea dike protection of the tree planting formula in coastal salinity inundated areas. Forestry University of Vietnam, Ho Chi Minh City, Vietnam.
- SPGMEC (Soonabai Pirojsha Godrej Marine Ecology Centre) (2015) *Mangrove Ecology*. SPGMEC, Mumbai, India. See <http://www.mangroves.godrej.com/mangroveecology.htm> (accessed 10/02/2015).
- Stulz R and Mukerji K (1988) *Appropriate Building Materials: A Catalogue of Potential Solutions*, 3rd edn. SKAT, St. Gallen, Switzerland.
- Tonneijck F and van Eijk P (2015) *Building with Nature for Coastal Resilience*. Wetlands International, Wageningen, The Netherlands. See <https://www.wetlands.org/publications/building-with-nature-for-coastal-resilience/> (accessed 02/03/2015).
- Verhagen HJ and Loi TT (2012) The use of mangroves in coastal protection. *Proceedings of 8th International Conference and Coastal and Port Engineering in Developing Countries, Madras*. IIT Madras, Chennai, India.
- Vijay R, Khobragade PJ, Sohony RA, Kumar R and Wate SR (2014) Hydrodynamic and water quality simulation of Thane Creek, Mumbai: an impact of sewage discharges. *Indian Journal of Geo-Marine Sciences* **3**(10): 519–526.