ENGINEERING ANALYSIS FOR A MANGROVE PLANTING SITE – TOWARDS A SUSTAINABLE COMMUNITY-ENGAGED COASTAL PROTECTION PROGRAM IN THE PHILIPPINES

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Abstract : Engineering methodologies are incorporated into community-based programs of mangrove rehabilitation in Panay Island that aim to provide viable protection to eroding typhoon-frequented Philippine coastlines. These involve analyses of storm waves and formulation of an engineering solution to promote calmer wave conditions around a pilot planting site. The study mainly involves the use of wave simulations to determine the wave loadings on the planting areas with site-specific data on winds, tides and seabed topography. Suitable design criteria based on the project's economic constraints and logistics are used to adapt the solution to the site. The incorporation of engineering approach into the project helps ensure a higher success rate in terms of mangrove survival rate and recovery of eroded backshore, as indicated by an initial post-construction monitoring of waves in the planting site and backshore sediment accretion.

Key words : mangroves, engineering analysis, rehabilitation, waves, typhoons

1 INTRODUCTION

Mangroves are semi-terrestrial habitats that afford natural protection to coastal areas by acting as buffer zones during typhoons and storm surges, mitigating the erosion of shorelines and riverbanks. Due to their unique root system, mangroves are known to be sediment interceptors (Hamilton and Snedaker, 1984) making them effective in the long-term stabilization of coastlines. Mangroves are also sources of various food products, such as fish, crustaceans and mollusks. Other mangrove-derived products include fuel (firewood, charcoal), leather products (dyes, tannins), construction materials (timber, poles), paper production raw materials, beverages (vinegar), drugs (alcohol, medicines), and forage for livestock (Primavera, 2000). Kapetsky (1987) estimated the annual production of mollusks, fish, shrimps and crabs from the total mangrove area of 171,000 km^2 in 1985, and reported that about 462,200 fisher folk derived livelihood from these mangroves.

Despite the many uses of mangroves and the shore protection they provide, mangrove areas along coastlines have dwindled through the years. In the Philippines, mangrove coverage has declined from an estimated 500,000 ha in the early 20th century (Brown and Fisher, 1918) to 132,500 ha in 1990 (Auburn University, 1993), which is equivalent to an average yearly loss rate of 4.7 ha. This decline has been accompanied by an increase in aquaculture production, which converted an estimated 141,000 ha of mangrove areas into brackish water ponds in the period 1988-1990 for fish and shrimp production (Primavera, 1995).

In more recent years, efforts have been exerted to attempt to reverse this anthropogenic process by implementing rehabilitation programs, including setting up inland nurseries and transplanting of mangrove seedlings into the natural environment. However, these traditional efforts have resulted in low success rate, mainly because the transplants are destroyed before reaching their minimum resiliency stage to withstand the natural environmental forces.

This study aims to present an approach to incorporate engineering methodologies into the mangrove rehabilitation efforts. The approach has been applied to one of several mangrove rehabilitation sites in the Visayas, where erosion is particularly severe and waves negatively affect the survival of newly planted mangroves. A scientific approach is adopted by examining the wave climate of the proposed planting area. Numerical analyses of the wave and tide loadings are carried out and synthesized, with the aim of locating wave energy concentration zones that may need suitable wave breakers to protect the mangrove saplings over a short-term period. In this manner, the coastal protectors are protected while growing to their minimum resiliency stage.

Section 2 of this paper presents a discussion of mangrove functions in coastal protection. A brief discussion of mangrove rehabilitation activities then follows. The project site and available data are discussed in Section 3. Section 4 presents typhoon data and Section 5 focuses on the hydraulic analyses of their induced waves. Section 7 discusses the engineering design of the protective structures. Section 6 briefly discusses the design implementation and post-construction monitoring.

2 MANGROVES IN COASTAL EROSION PROTECTION

Fully-grown mangroves (see Figure 2) provide natural protection to the coasts by acting as energy dissipation zones of waves that would otherwise approach the coast with full force. Due to their intricate semi-terrestrial root system, they are also able to trap littoral sediments and thereby stabilize the coastline. Considering the significant decline of mangrove coverage in the country and recent alarming natural disasters, a community-based project has embarked on a program to rehabilitate mangroves in presently unsuccessful planting zones and to plant mangrove saplings in new pilot areas. Due to the low success rate of earlier rehabilitation programs where the saplings were immediately exposed to the wave environment, it was recognized that protection works must be in place prior to transplanting from inland nurseries.

Full-grown mangroves are able to protect vulnerable shores against high waves by causing them to break. Such breaking allows only the smaller waves to reach the shore. Since waves usually approach from various directions on most open-sea shores, some waves may impinge on mangroves without breaking. Fortunately, energy dissipation of these waves normally occurs through fluid friction around the plants' trunk and other surfaces, the intensity of which increases with the size of the plants and the height of the impinging waves. Energy dissipation is also afforded by the fluid turbulence generated in the interstitial spaces of these plants by the entrainment of air when waves and currents impinge on them.

It is known that mangroves are affected more directly by the physical, rather than the biological, environment. The frequency of tidal inundation appears to exert primary influence on their growth and propagation, with about 30 percent annual submergence in the tides as a maximum threshold for their survival. The depth of sediment cover also influences their survival and propagation, as this directly affects the metabolic respiration through the pneumatophores, or the root system. Some species of mangroves are capable of innately propagating along the coasts under ambient conditions of tides, waves and sediments, i.e. non-typhoon conditions On the other hand, growth of young mangrove saplings can be stunted even by ambient waves; in some cases, they are destroyed before reaching the minimum resiliency level when exposed to a harsh physical environment, e.g. nearshore areas frequented by typhoons and tropical storms. In order for these young mangroves to survive, it is necessary to choose a planting area where high waves are dissipated by natural wave breaking or shallow-water transformations. In case such ideal location is impossible to find, mangrove planting sites must be located in a wave shelter, that is, where energy dissipation of both ambient and extreme waves is deliberately induced through an impinging structure, such as a breakwater, submerged breakwater or artificial reef, by forcing these waves to break on the structure.

3 COMMUNITY-ENGAGED MANGROVE REHABILITATION PROGRAM

A number of organizations have initiated rehabilitation programs to reverse the depletion of mangrove areas in a number of countries in Southeast Asia. In the Philippines, these efforts are undertaken in cooperation with various stakeholders, including the local government unit, the coastal community residents, fisher folks and their organization, environment and natural resources agency, public works agency, industry organizations representing farmers and other workers with stake in agricultural and aquaculture productions, and local community organizers. These community-based efforts to rehabilitate mangroves typically involve inland nursing of seedlings or "wildings" around mother mangrove trees, subsequent coastal transplanting or "out-planting" of young mangrove saplings, and fencing off the area with bamboo or similar inexpensive indigenous materials (Primavera, 2004). However, they sometimes fail to ensure mangrove survival, resulting in low success rate of rehabilitation activities. To increase the success rate of these programs, an engineering component is incorporated into the rehabilitation efforts by undertaking a quantitative analysis of the wave climate to identify suitable planting areas for coastal mangroves. In cases where it is found that existing planting sites are in harsh wave environment, the results of the analysis will be used to determine the appropriate intervention and carry out its design and implementation.

A pilot site to implement an engineering component to the rehabilitation program was selected based on comparison of existing mangrove sites mostly in the Visayan Islands and a few in southern Luzon. This site was chosen because it is known to be exposed to tropical storms and typhoons, resulting in severe erosion rates. This mangrove rehabilitation project will benefit initially the coastal communities of Panay and Guimaras Islands (Figure 1) by providing coastal protection against the high waves, providing agricultural workers additional raw materials for food and other uses, and provide increased livelihood to farmers and fishermen. Due to the active participation of all stakeholders, the project is deemed to be sustainable in the long term.

4 PROJECT DESCRIPTION AND DATA

The pilot site for the deployment of mangrove protective structures is along the coastline of Panay Island (Figure 1). Existing planting areas are located inside Pedada Bay (Figure 1) which partially provides protection against waves during non-storm season. However, the same bay faces Sibuyan Sea which is frequented by typhoons. Such location allows high waves during typhoons to penetrate the bay and erode the interior coastline, a condition to which the low success rate of the mangrove transplanting activities is attributed. Fully-grown trees of a local mangrove species called "pagatpat" (Figure 2), which are generally found as front-liners in other thriving coastal mangrove sites, are found in significant numbers along either side of the proposed planting areas, but are nonexistent in the central zone. Previously built crib-like concrete structures called "modules" (Figure 3), intended to protect young saplings while promoting fish breeding, proved ineffective in promoting a calm zone for mangrove saplings to thrive. Either as a result or cause of the death of transplanted mangroves in this area, fishermen now find use for this foreshore zone as a boat dock (see Figure 2, right).

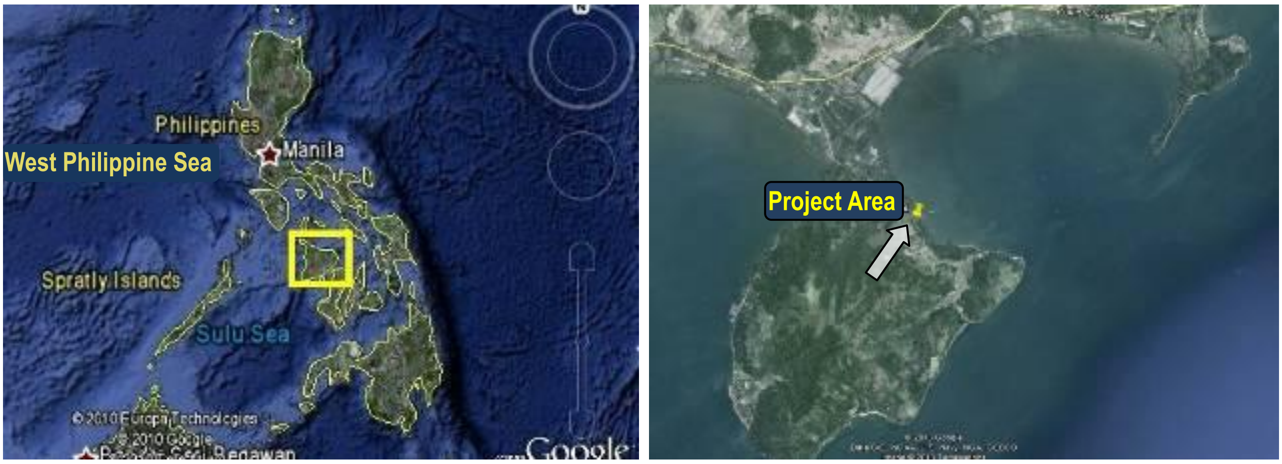

Figure 1 Project national location (left), Pedada Bay (right) (source: Google Earth)

Figure 2 View from inland of project bay (left), and of fully-grown mangroves to the north (middle) and south (right) coasts at low tide

Figure 3 (left) Damaged "modules"; (middle) closer view of a module; (right) mangrove seedlings in inland nursery

4.1 Tide Data

Astronomic tides primarily determine the prevailing water levels in the foreshore zone where the planting areas are located. Based on a 30-year record at the nearest tide station (NAMRIA, 2009), these water levels have a mean tidal range of 2.1 m, with the mean high tide and mean low tide almost equally displaced from mean tide level; the other tide statistics are shown in Table 1. These data are used, among others, in determining the most inland extent of the shoreline for input in the nearshore wave simulations, and in determining the seaward limit of the wave breaking zones.

Prevailing winds are characterized through the wind rose diagram shown in Figure 4 (left), showing the annual frequency and directional distribution of surface winds at the closest inland wind station. The diagram indicates that surface winds are dominantly southwesterly-northeasterly, which is consistent with the seasonal "Amihan-Habagat" wind patterns of the archipelago. Prevailing surface wind speeds can be moderate (up to 8 m/s) and very infrequently strong (up to 12 m/s).

Table 1 Tide characteristics

Mean Higher High Water MHHW	Mean High Water MHW	Mean Tide Level MLW	Mean Low Water MLW	Mean Lower Low Water MLLW
+1.07	+0.77	0.0	-0.80	-1.04

4.2 Prevailing Winds and Tropical Storms

The eastern sea fronting the project bay is frequented by tropical storms and typhoons. Table 2 summarizes the strongest historical typhoons that tracked this sea. The tracks of two of these typhoons, which are found below to be the critical cases for the site, are shown in Figure 5 (bottom); as shown, typhoons in the east-bounding sea are generally produced in the Pacific Ocean. Together with the computed wave fetches and information on the wind station, these data are used to predict the growth of storm-induced waves in deep water and to hindcast the extreme historical waves that most likely approached the project coastline.

Table 2 Strongest tropical cyclones

Date	Tropical Cyclone	Highest wind (mps)	Direction
Oct-28-1995	Super Typhoon Rosing	36	SW
Dec-10-1951	Typhoon Amy	34	NE
Apr-25-1971	Typhoon Diding	25	SE
Jul-28-1982	Typhoon Iliang	25	SSW

Figure 4 (left) Annual prevailing winds; tracks of Typhoons Amy (middle) and Diding (right)

5 HYDRAULIC ANALYSIS OF WAVE LOADINGS ON MANGROVE PLANTING SITE

Wave conditions in the offshore deepwater can be estimated from surface wind data at the wind station, wave fetch and the duration of the wind. For prevailing waves, wind duration does not limit the height and period of offshore waves. To determine the storm-induced wave fields in the shallower nearshore zone where the mangrove planting site is typically located, a wave transformation model is numerically implemented. A special case of a nonlinear wave model developed for a porous seabed on arbitrary bathymetry (Cruz et al., 1997) is used for this purpose. This special Boussinesq-type wave model considers the seabed to be impermeable, and can be written as:

$$\frac{\partial \eta}{\partial t} + \nabla \cdot \left[\mathbf{u}(h+\eta) \right] = 0 \quad (1)$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} + g\nabla\eta + \frac{h^2}{6}\left(\nabla\cdot\frac{\partial \mathbf{u}}{\partial t}\right) - (\tfrac{1}{2}+\gamma)h\nabla\left(h\nabla\cdot\frac{\partial \mathbf{u}}{\partial t}\right) - \gamma g h\nabla\left[\nabla\cdot(h\nabla\eta)\right] + \mathbf{F}_b + \mathbf{F}_s + \mathbf{F}_w = 0 \quad (2)$$

where $\eta(x,y,t)$ is the water surface displacement from still water level, $\mathbf{u} = (u,v)$ the depth-averaged fluid particle horizontal velocity vector, (x, y) the horizontal coordinates, t time, $\nabla = (\partial/\partial x, \partial/\partial y)$ the horizontal gradient operator, γ the frequency dispersivity extension factor, g the gravity acceleration, $\mathbf{F_b}$ the wave-breaking energy-dissipation term, $\mathbf{F_s}$ the structure-induced damping term, and $\mathbf{F_w}$ the bottom friction term. Eqs. (1) and (2) are respectively the continuity and momentum equations formulated for nonlinear and dispersive water waves. With $\gamma = 1/15$, the model has an extended frequency dispersion range and can therefore be used for relative depths (h/L_O) ranging from the lower limit of deep water ($h/L_O = 0.5$) to the shallow waters fronting the project area. This special wave model has been applied to study the wave climate in coastal harbors (Cruz, 2007).

A primary data needed in the wave loading analyses is the distribution of water depths, or bathymetry, around the planting areas. For this purpose, a bathymetric geodetic survey was commissioned. Raw data of existing water depths at various locations on an irregular grid (shown as the number marks in Figure 7), are used to obtain contours of still-water depths, which are plotted in simulation output graphics below. These data are consolidated with available spot depths from 1:50,000 scale offshore topographic map (NAMRIA Topographic Map Central Philippines), which are then jointly digitized as raster depth data to be inputted into the wave simulations.

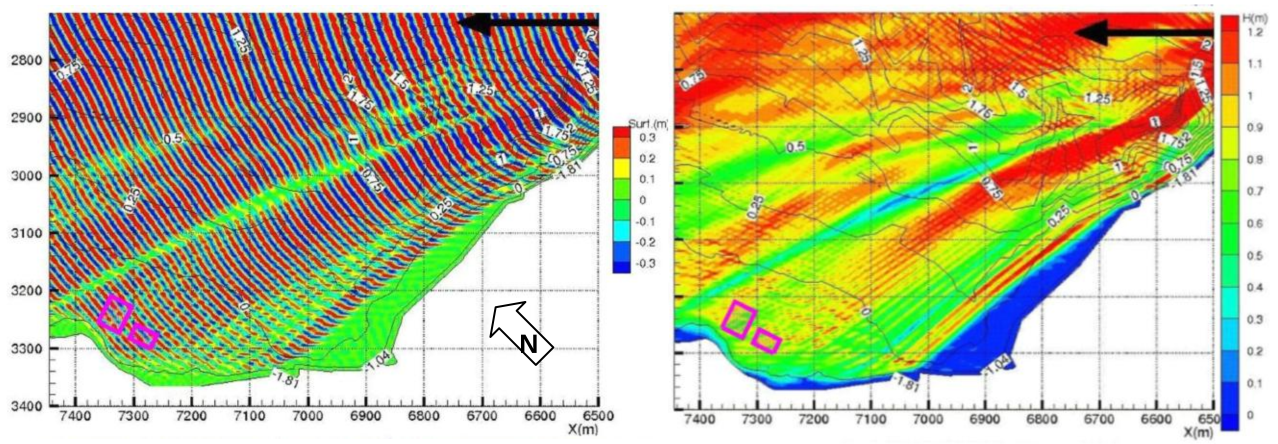

Figure 5 Waves generated by Typhoon Diding approaching from southeast at high tide: (left) water surface snapshot, (right) resulting wave height distribution

The nearshore wave fields generated by the 4 historical typhoons shown in Table 2 have been simulated using the above model, digitized bathymetry, and hindcast offshore wave conditions. It is found that Typhoons Amy and Diding are most critical to the project coast. Figure 5 shows the simulated wave fields, i.e., water surface snapshot and resulting wave heights, for Typhoon Diding which generated offshore waves that approached from the southeast. The water level in the simulations is set to MHHW to account indirectly for the storm surge (note that the rectangles indicate the proposed planting areas). Patterns of wave energy concentrations and divergence are revealed by these plots.

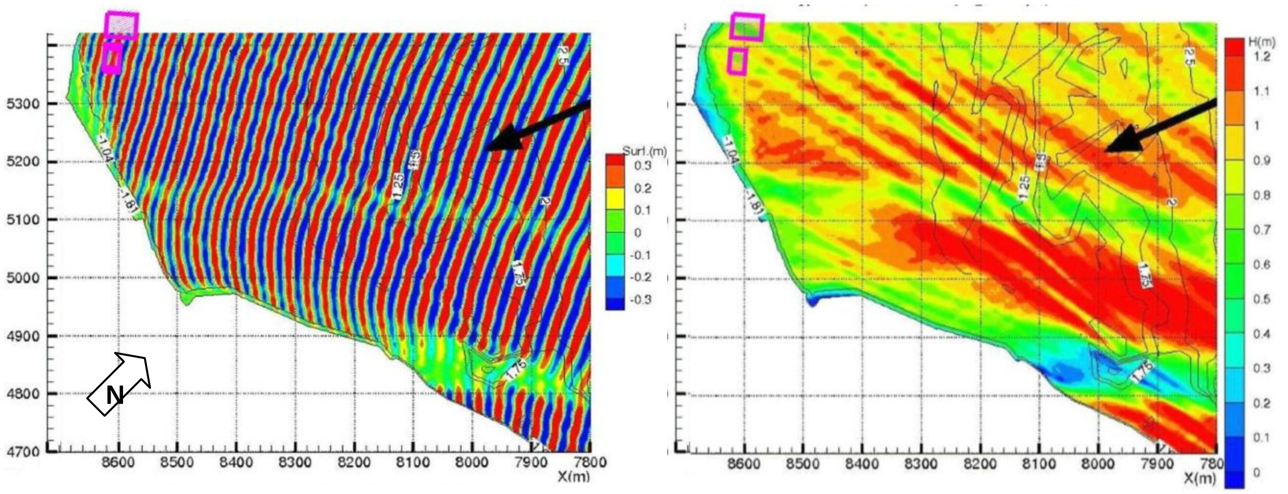

Figure 6 Waves generated by Typhoon Amy approaching from northeast at high tide: (left) water surface snapshot, (right) resulting wave heights

Figure 6 shows the wave fields due to Typhoon Amy which induced offshore waves approaching from the northeast. Due to the two smaller islands to the northeast of the bay entrance, the local waves are strongly diffracted, resulting in strong penetration of wave energy into the bay, including the site’s nearshore zone.

6 ENGINEERING DESIGN OF PROTECTIVE STRUCTURES

Coastal structures are normally designed to withstand extreme waves, i.e. due to typhoons. A synthesis of all simulated cases of typhoon-induced waves indicates that a detached breakwater fronting the planting areas will provide protection to the mangrove saplings. Considering the requirement of an entranceway for fishing boats and the effects of the structures on wave-and tide-induced circulations, two nearshore breakwaters with a gap are laid out as shown in Figure 7. Their orientation and length are based on the wave approach directions and distribution of local wave heights.

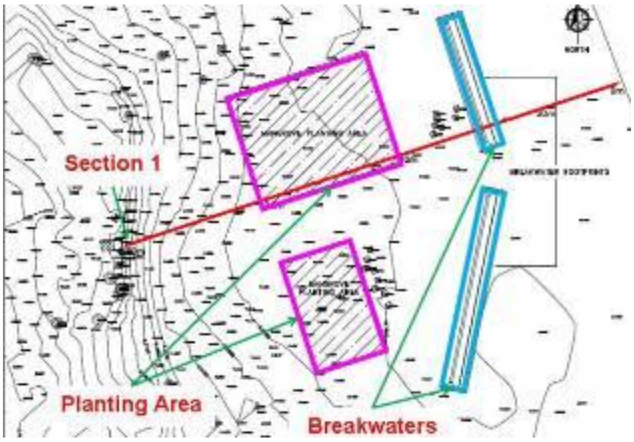

Figure 7 Location of planting zones and breakwaters

The required median size (kg) of armor stones is determined from the semi-empirical formula (USACE, 2004) as follows:

$$M_{50} = \frac{\rho_r H^3}{\left(\frac{\rho_r}{\rho} - 1\right)^3 K_D \cot\alpha} \tag{3}$$

where ρ_r is the mass density of the armor stones, ρ the density of water, H the design wave height, α the angle of the armor slope, and K_D the stability coefficient of the armor stones.

Based on data of climatological extremes, the apparent recurrence intervals of the critical typhoons are about 54 and 34 years. When the results shown in Figures 5 and 6 are used to layout and design the protective breakwaters, the required median mass of the armor layer (see Figure 8) comes out to be about 500 kg. Unfortunately, such large stones cannot be sourced close to the site. Furthermore, this community-based project prefers to utilize manpower that is already available from the workers in the project's organizations. Also considering the useful life of the protection of 5 years, which is just sufficient for the saplings to grow big enough to withstand the waves, the initial structure size is deemed unsuitable to the project objectives.

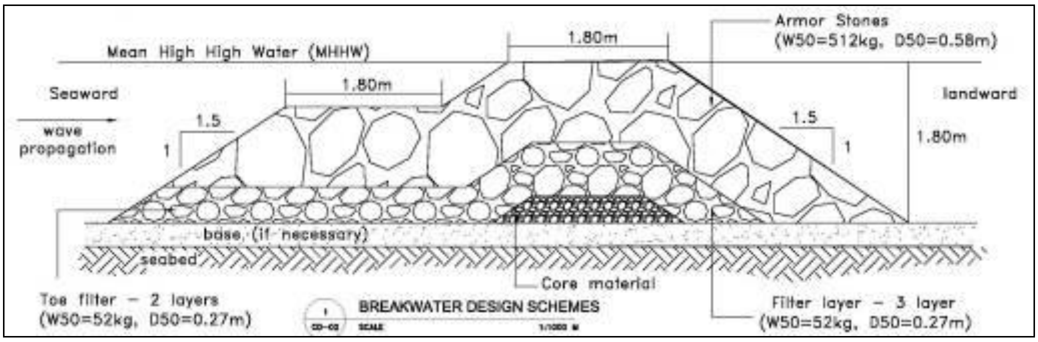

Figure 8 Full wave-loading breakwater cross-section

To obtain an engineering design of the mangrove protection that is best suited to the characteristics of the pilot site and to the project objectives, the following design conditions were adopted: (a) a useful life of 5 years, which is deemed sufficient to provide protection over the minimum resiliency period of 2 to 3 years from transplanting; (b) a reduced design water level based on the mean tide; (c) allowable local wave height of 20 cm at the planting areas; and (d) width of passageway for fishing boats of about 18 meters. With these design conditions, wave field simulations were again carried out. Figure 9 shows the resulting wave heights for the critical cases of typhoon-induced waves approaching from the southeast and northeast. It is clear that the local waves around the contemplated planting areas are significantly reduced from those in Figures 5 and 6.

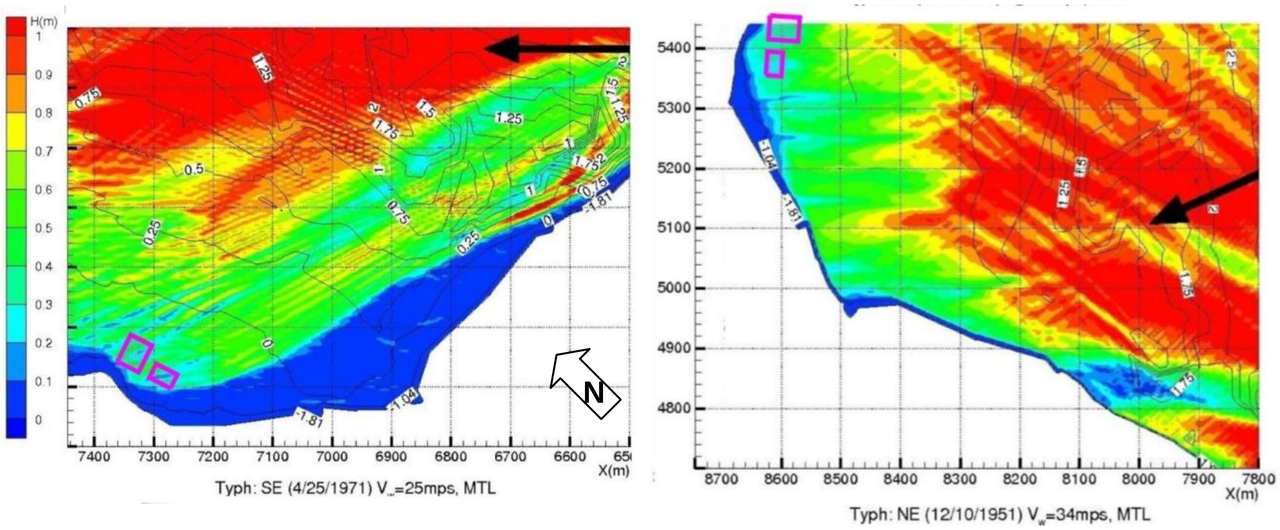

Figure 9 Wave heights due to (left) Typhoon Diding and (right) Typhoon Amy, at mean tide level

The results in Figure 9 have been adopted in the design of the breakwaters. A preliminary layout was designed and subjected to post-implementation wave simulations, some results of which are shown in Figure 10. It is seen that some wave energy will penetrate the gap into the planting areas when exposed to Typhoon Amy, i.e. extreme waves from northeast. However, the local waves will not be higher than 20 cm.

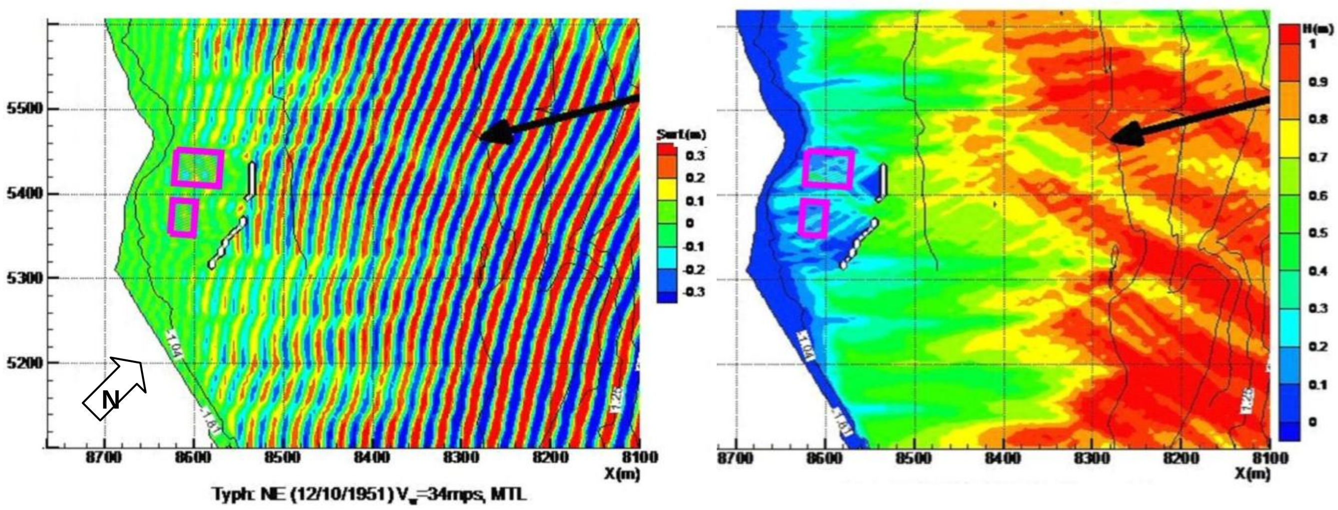

Figure 10 Waves due to Typhoon Amy at mean tide: (left) water surface snapshot, (right) resulting wave heights

The recommended plan-form layout of the mangrove protection, shown in Figure 7, consists of two detached breakwaters of the rock-mound type, consisting of an armor layer, filter layer, toe protection and core materials. A base layer is optional depending on the existence of suitable seabed material. Two alternative breakwater cross-sections are shown in Figure 11. The first is a traditional rubble-mound breakwater with 120-kg armor stones, which are available near the site and can be carried by men without hauling equipment. The other is a modified mound breakwater with armor stones of the same size, but with gabions at the lee side; this section reduces the quantity of the larger armor stones, in exchange for requiring the smaller core stones to be enclosed by a wire mesh. The cost of this second design depends on the durability requirement of the wire mesh; regular non-galvanized mesh will probably withstand 3 years of marine water-induced corrosion without replacement or expensive coating treatment. Mainly on account of maintenance requirements and material cost, the first alternative was selected by the project organizers.

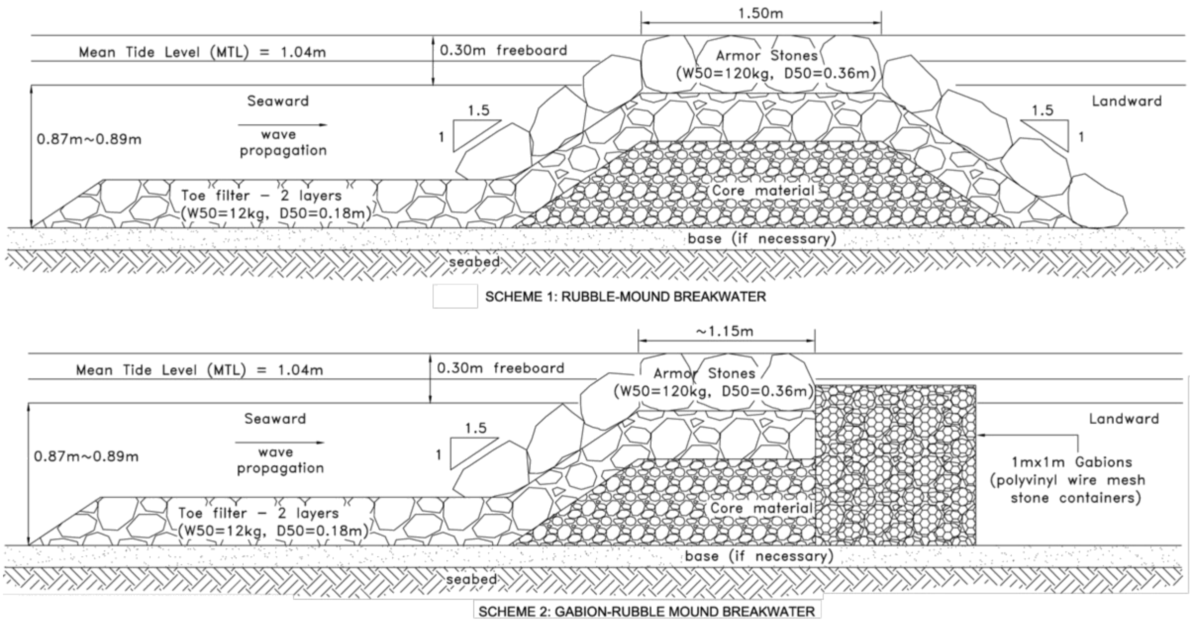

Figure 11 Reduced-loading breakwater alternatives: (top) rock-mound type, (bottom) mound-gabion breakwater

7 PROJECT IMPLEMENTATION AND MONITORING

7.1 Construction of Breakwaters

Construction of the breakwaters was facilitated by the non-governmental organization in cooperation with engineers from the provincial office of the public works department DPWH. The community stakeholders also helped by providing manpower, hauling tools, logistics, and work coordination. Actual construction was started immediately after approval of the final design scheme prior to the onset of the northeast monsoon. Portions of the old and damaged “modules” were removed to avoid undesirable wave effects outside the breakwater-protected foreshore. Figure 12 (left) shows the manual placement of rocks on the armor layer of one of the almost-complete mound breakwaters. The entranceway for fishing boats can be seen.

7.2 Monitoring of mangrove saplings’ growth and sediment accretion

After 26 months and 4 seasonal changes, the breakwaters have caused visible changes in the nearshore landscape of the planting zone (Figure 12, right). In particular, coastal sediments have accreted in the shadow zones of the structures as a result of calmer wave conditions. The aggraded zones have been used as mangrove transplanting areas. The transplanted mangroves appear healthy and the eroded coasts further inland have shown significant recovery from erosion. If the transplanted mangrove saplings are able to withstand the harsher wave and wind environments of typhoons within at least 5 years, the protective breakwaters can be dismantled as the saplings are assumed to be robust enough for such environment. It should be noted that the breakwaters are temporary, as the rocks are merely piled on top of each other and not cemented.

Figure 12 (left) Breakwaters completed in 2010; (right) accreted sediments after 26 months, mangrove saplings transplanted, and fully grown mangroves seen in the background (ZSL-CMRP photos by J.H. Primavera (left) and A.M. Torrechilla)

Figure 13 compares the backshore elevations before and after the breakwater construction (2010 versus 2012). A concrete road used to exist along the alignment indicated by the arrows, but was eventually eroded by ambient and storm waves. At this location, visible accretion of silt has been observed after construction. A geodetic survey was conducted to quantify the ground elevation. The results of this survey have been plotted in Figure 14 (right) with the pre-construction data along a transect through the southern breakwater (Figure 14, left). In general, an average accretion of about 20 cm is experienced over a cross-shore distance of about 100 m nearest the breakwaters. Further into the backshore near the eroded road location, accretion is about 5 to 10 cm.

Figure 13 Backshore elevation before and after breakwater construction (ZSL-CMRP photos by J.H. Primavera)

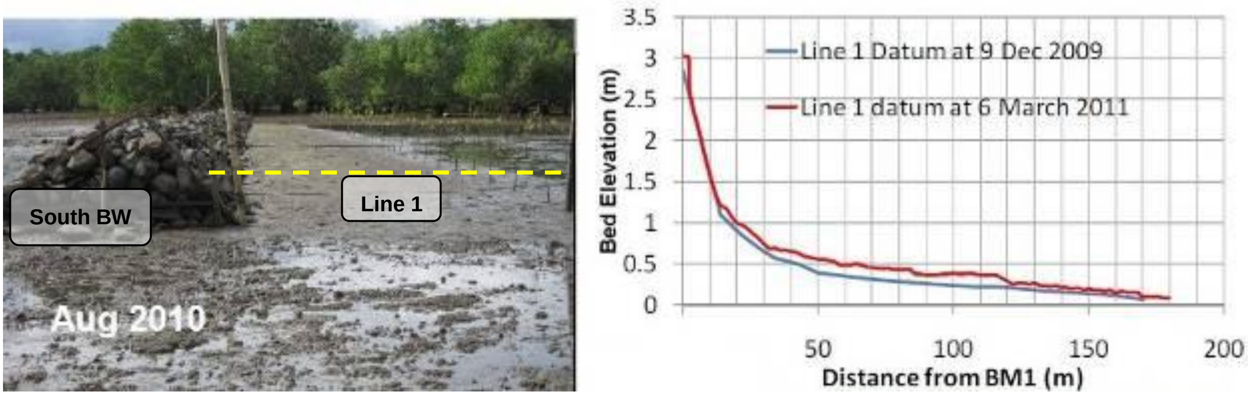

Figure 14 Measured post-construction accretion behind the breakwaters (ZSL-CMRP photo by R.V. Joven; Mar 2011 data from UP-MSI).

8 CONCLUSIONS

It is found from this study that engineering methodologies are needed to increase the likelihood of success of mangrove rehabilitation activities. These include gathering data of tides, prevailing winds and typhoons, and conducting bathymetric survey around the contemplated planting areas. In order to quantify the extreme wave loadings due to typhoons and possibly explain causative mechanisms for unsuccessful transplanting sites, it is necessary to carry out numerical modeling and wave loading analyses of the site’s nearshore area. A synthesis of these simulative analyses will help identify unsuitable planting areas and lead to the formulation of high-wave hazard mitigating schemes or engineering solutions. In existing mangrove areas exposed to a harsh wave environment, an engineering approach is imperative in studying the proper course of intervention, and in designing a suitable protective structure when found necessary.

The above engineering methodologies have been applied to the pilot site of a typhoon-tracked mangrove planting area in Panay Island. The above methodologies were further used to eliminate unfeasible or uneconomic options, adapt the identified mitigating solution to the project objectives in terms of economic cost and project logistics, and validate the effects of the selected solution prior to construction implementation. In totality, these methodologies will help ensure the success of the mangrove rehabilitation program for this pilot site.

A post-construction evaluation over a 2-year period indicates that the solution is initially effective on the basis of the project’s objectives. A longer-term monitoring will help in evaluating the overall soundness of the solution implementation.

ACKNOWLEDGMENT

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