

HYDRAULIC ANALYSIS OF A MANGROVE PLANTING ZONE FOR MITIGATION OF TYPHOON-INDUCED COASTAL EROSION

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ABSTRACT: Fully-grown mangroves provide natural protection to the coasts against waves and currents and stabilize the shorelines. However, young mangrove saplings transplanted onto coastal areas often die when immediately exposed to the natural wave environment. To increase the survival rate of mangrove transplants, engineering solutions are incorporated into traditional mangrove rehabilitation program. This study involves the analysis of the wave loading on protective structures for a typhoon-frequented coastal mangrove area, which is the pilot site for a planting zone of a community-engaged mangrove rehabilitation program. Engineering design and implementation of the solution are also discussed.

Keywords: Mangroves, coasts, erosion, waves, typhoons

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. 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), agriculture (fodder, lime), paper production, 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 km² 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). These findings indicate an average mangrove loss rate of 4.7 hectares per year, which is a high rate considering climate change and the increased hazards and risks in coastal areas. The last two decades saw a dramatic increase in mangrove area conversion into brackish-water ponds. In fact, in the period 1988-1990, there was a sharp decline of 141,000 hectares of mangrove coverage, accompanied by an increase in aquaculture production via brackish-water ponds for fish and shrimp production (Primavera, 1995).

MANGROVE PLANTING ZONES FOR COASTAL EROSION

Fully-grown mangroves (Fig. 1) provide natural protection to the coasts by acting as energy dissipation zones of waves that would otherwise approach the coast with full force. . Studies also report on their ability to intercept sediments (Hamilton and Snedaker, 1984) due to their intricate and unique root system that enables them to trap littoral sediments and thereby stabilize the coastline. In view of the significant decline of mangrove coverage in the country and recent alarming natural disasters, a community-engaged movement 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.



Fig. 1 Fully-grown coastal mangrove

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To increase the success rate of the existing rehabilitation program, it is necessary to provide temporary protection to young mangrove saplings during the early growth stage in their final environment. Once pilot planting zones are determined according to bio-physical criteria, the need for protection against waves is assessed from engineering analysis of the storm-induced wave climate at the site. This study focuses on the application of numerical simulations to determine the wave loading on a pilot mangrove planting zone, the development of design criteria and subsequent design of protection works to ensure a high survival rate of mangrove sapling.

Mangrove rehabilitation programs have been implemented in some areas of the archipelago. They generally follow the traditional method beginning from selection of the planting zone based on biological, ecological and physical criteria; inland nursing of saplings; transplanting; and finally monitoring of the growth progress of the saplings. Cases of both healthy and problematic planting zones have been documented. However, the success rate of these rehabilitation activities, when defined as the percentage of transplants that grew and became trees, is quite low, with a few sites having as low as 15% success rate.

This study aims to provide engineering inputs to efforts aimed at increasing the success rate of mangrove planting areas. In the documented unsuccessful planting sites, the common condition was that the saplings, after transplanting, are immediately exposed to the natural wave environment. The saplings did not reach the minimum resiliency growth stage because during the first one to three years, the site was tracked by a tropical cyclone with harsh wave loadings, or that the planting area itself is prone to large and turbulent wave forces due to shoaling, breaking, and/or swashing waves. The paper discusses a project case where the engineering solution is applied.

PROJECT DESCRIPTION AND DATA

The pilot site for the deployment of mangrove protective structures is along the coastline of Panay Island (Fig. 2). Existing planting areas are located inside a bay (Fig. 3), which partially provides protection against waves during non-storm season. However, the same bay faces to the east a sea that is frequented by typhoons, a condition to which the low success rate of the mangrove transplanting activities is attributed. Zones of a local mangrove species called “pagatpat” (Figs. 1, 4), which are generally found as frontliners 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 area. Previously built

crib-like concrete structures called “modules” which were intended to protect young saplings while promoting fish breeding, proved ineffective. 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 Fig. 3, lower right).



Fig. 2 Project location



Fig. 3 The project bay, with fully grown mangroves along the sides



Fig. 4 Mangrove saplings in nursery

Astronomic tides primarily determine the water levels in the foreshore zone, where the planting areas are located. Based on a 30-year record at the nearest tide station, 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 tide statistics are shown in Table 1. These data are used 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.

Table 1 Tide characteristics

MHHW	MHW	MTL	MLW	MLLW
+1.07	+0.77	0.00	-0.80	-1.04

Prevailing winds are characterized through the wind rose diagram shown in Fig. 6, showing the annual frequencies and directional distribution of surface winds at the closest inland wind station. The diagram indicates that 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, that is, up to 8 m/s.

HISTORICAL TYPHOONS

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 Fig. 6. 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 coast.

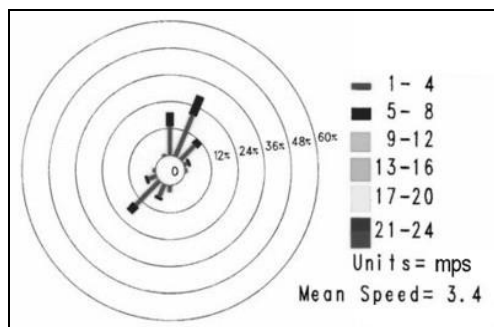


Fig. 5 Annual wind rose diagram

Table 2 Strongest tropical cyclones

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

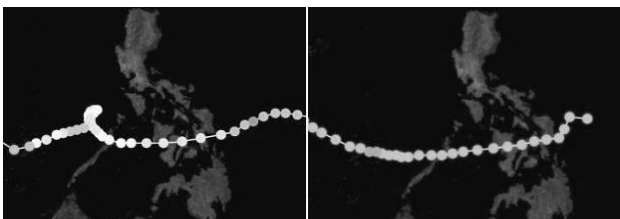


Fig. 6 Tracks of Typhoons Amy and Diding

HYDRAULIC ANALYSIS

In order to determine the storm-induced wave fields in the site’s nearshore zone, 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 Boussinesq-type wave model considers the seabed to be impermeable, and can be written as:

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

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

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. With $\gamma = 1/15$, the model has an extended frequency dispersion range and can therefore be used for relative depths (h/L_0) ranging from the lower limit of deep water ($h/L_0=0.5$) 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).

The primary data needed in the wave loading analyses is the bathymetry around the planting areas. For this purpose, a bathymetric survey was commissioned. Raw data of existing water depths at various locations on an irregular grid are used to obtain contours of still-water depths (Figs. 7 and 8). These data are consolidated with available spot depths on Namria’s published bathymetric maps, which are then jointly digitized as raster depth data as input to the wave simulations.

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 coastline. Fig. 7 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 rectangles indicate the proposed planting zones). The water level is set to MHHW to account indirectly for the storm surge.

Patterns of wave energy concentrations and divergence are revealed by the plots.

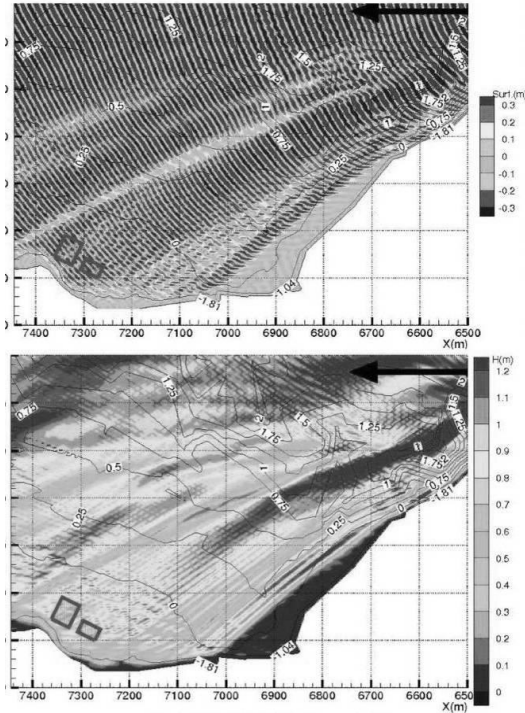


Fig. 7 Waves generated by Typhoon Diding (SE) in the nearshore area at high tide: (top) water surface snapshot, (bottom) wave heights

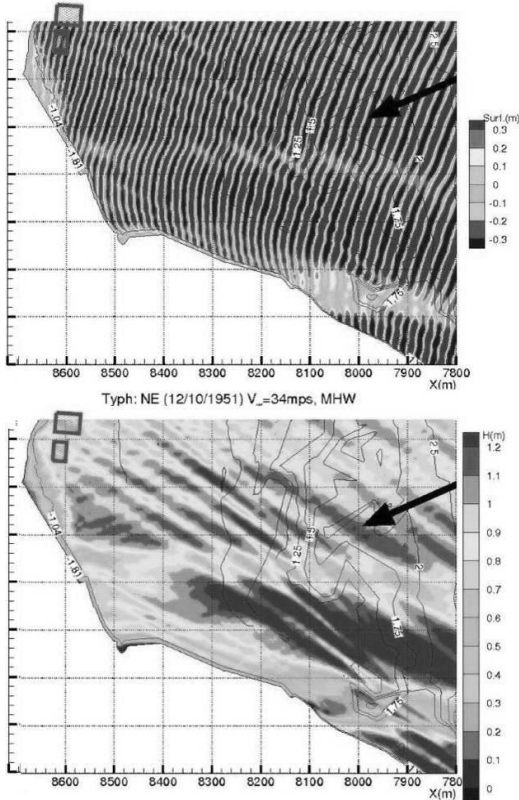


Fig. 8 Waves generated by Typhoon Amy (NE) in the nearshore area at high tide: (top) water surface snapshot, (bottom) wave heights

Figure 8 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, the local waves are strongly diffracted, resulting in stronger penetration of wave energy, i.e. higher waves, inside the bay, including the site's nearshore zone.

DESIGN OF MANGROVES' PROTECTION

Coastal structures are normally designed to withstand extreme waves, i.e. typhoon-induced waves. 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 transplants. 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 Fig. 9. Their orientation and length are based on the wave approach directions and distribution of local wave heights.

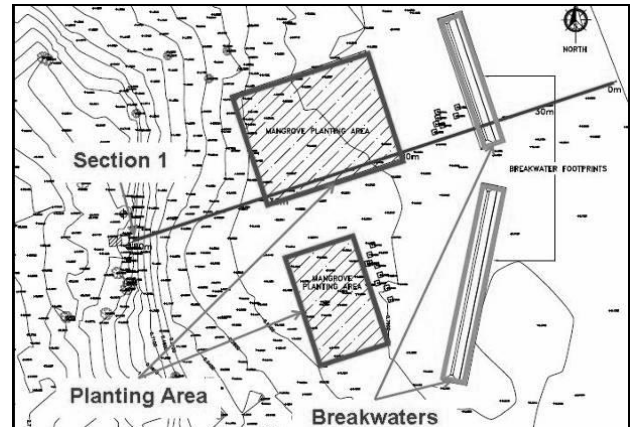


Fig. 9 Bathymetric contours, location of planting zones and breakwaters

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

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

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 Figs. 7 and 8 are used to layout and design the protective

breakwaters, the required median mass of the armor layer (Fig. 10) comes out to be about 500 kg. Unfortunately, such large stones cannot be sourced close to the site. Also, this community-based project prefers to utilize manpower that is already available from the workers in the supporting peoples' 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.

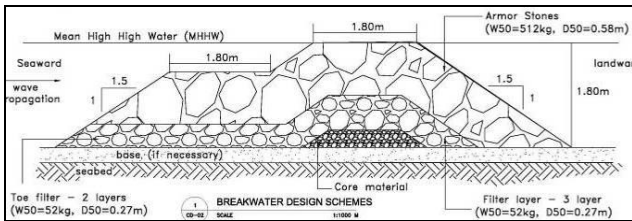


Fig. 10 Full-load breakwater cross-section

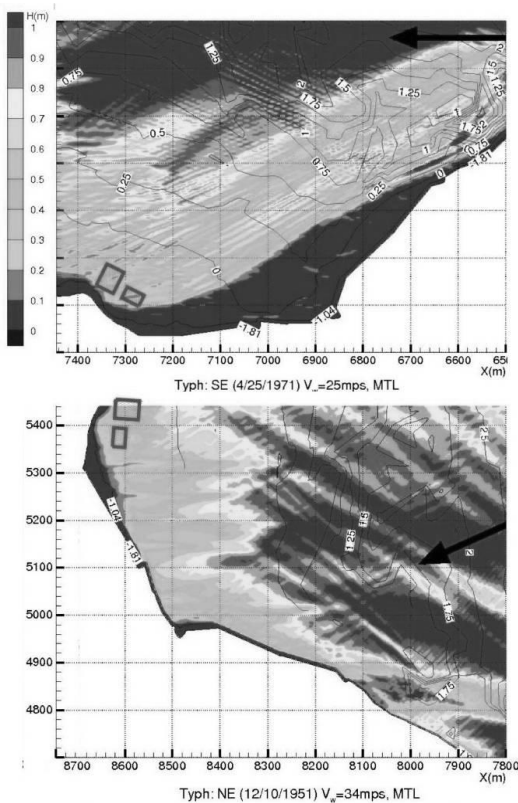


Fig. 11 Wave heights induced by (top) Typhoon Diding and (bottom) Typhoon Amy at mean tide level

To obtain an engineering design of the mangrove protection that is best suited to the characteristics of the pilot site as well as the project objectives, the following design conditions were adopted: (a) an anticipated 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) an unobstructed passage width for fishing boats of about 18 meters. With these design conditions, wave field simulations were again carried out. Fig. 11 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 Figs. 7 and 8.

The results in Fig. 11 have been adopted in the design of the breakwaters. A preliminary layout was designed and subjected to post-construction wave simulations, some results. One such result is shown in Fig. 12, where 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.

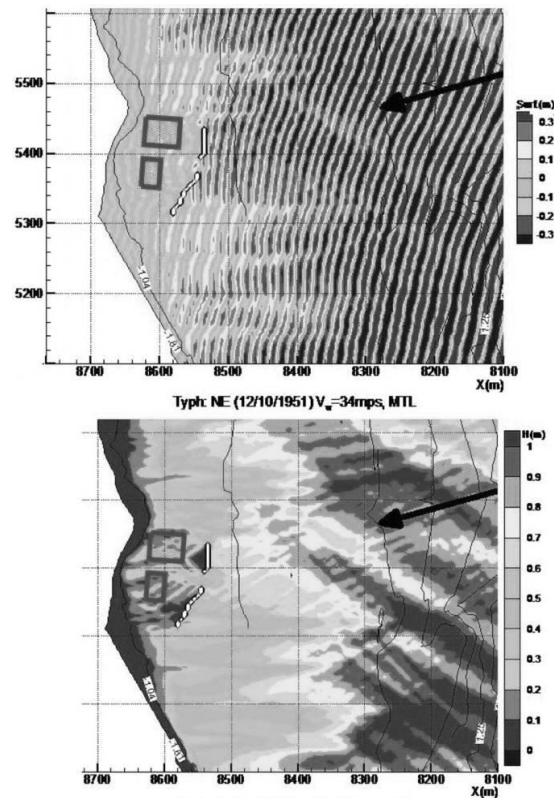


Fig. 12 Waves generated by Typhoon Amy in the nearshore area: (top) water surface snapshot, (bottom) wave heights

The recommended plan-form layout of the mangrove protection (see Fig. 9), 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. An alternative breakwater cross-section, shown in Fig. 13, has been designed for the reduced loading. This section is a

traditional rubble-mound breakwater with 120-kg armor stones, which are available near the site and can be carried by men without the need for hauling equipment.

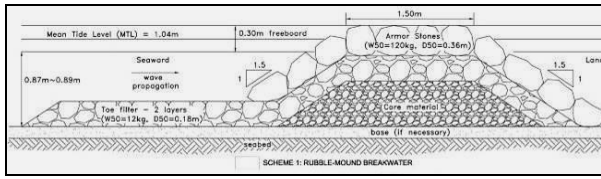


Fig. 13 Rock-mound breakwater cross-section for reduced wave loading

SOLUTION IMPLEMENTATION AND ASSESSMENT

Figure 14 shows a view from inland of the pair of completed breakwaters at mean tide. The entranceway and interim docking areas for fishing boats are also visible. Portions of the old and damaged “modules” were removed to avoid undesirable wave effects outside the breakwater-protected foreshore.

After 26 months and 4 seasonal changes, the constructed breakwaters have caused visible changes in the nearshore landscape of the planting zone. In particular, coastal sediments have accreted in the shadow zones of the structures as a result of calmer waves. The aggraded zones has been used as mangrove transplanting areas. The grown-up mangroves appear healthier too, 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.



Fig. 14 (top) Breakwaters completed in 2010; (bottom) accreted sediments after 26 months, healthy mangroves seen in the background

CONCLUSIONS

Based on this study and the pilot project implementing it, it is found that protective structures

should be integrated in mangrove rehabilitation programs to increase their certainty of success. The engineering design of the structures should not only be responsive to the wave loading at the site, but also meet the requirements of a community-led project in terms of cost and service life.

Engineering methodology is needed to increase the likelihood that coastal mangrove transplants, while still adjusting to their final environment, are protected from high waves. In meeting this objective, it is imperative to analyze the wave loading of historical typhoons through wave modeling, which will help identify the causative processes of high waves, eliminate unfeasible engineering solutions, and adapt the feasible ones to the project objectives.

ACKNOWLEDGEMENTS

The authors acknowledge Dr. Jurgenne Primavera for providing recent site photos (Fig.14).

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