THE USE OF MANGROVES IN COASTAL PROTECTION

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The objective of this research is to obtain generic relations between attenuated wave heights and various vegetation and topographical scenarios. Subsequently, it is aimed to find out what is the actual cost profit of a dike construction behind a mangrove zone comparing to the case when mangroves are absent. The graphs and formulas developed in this research may serve as a first approximation during feasibility studies or conceptual designs of a coastal dike incorporating mangrove vegetation. They allow calculating the design wave height attenuated by site specific or planned for restoration mangrove forests, for different design met-ocean conditions. Calculated wave reduction coefficients can be later on translated to the cost savings of a coastal dike raised behind the mangrove forests.

Keywords: mangroves, coastal dikes, cost,

INTRODUCTION

One of the solutions to reduce construction costs of a coastal dike is to decrease wave loads which directly result in using lighter revetment, lower crest level and subsequently smaller land use. In countries located in the tropical zone, one of the options to attenuate wave energy is to plant mangrove forests in front of a dike. Research on this topic e.g. Vos (2004), Quartel (2007), has proven the effectiveness of mangroves used in this way.

The vast majority of such studies were done with the consideration of only one or few species. In practice, mangrove forests are more diverse and consist of many different species. The species occur however in zones, which are groupings of the same species of mangrove within a whole mangrove forest. Example of such a zonation pattern is presented in Figure 1.

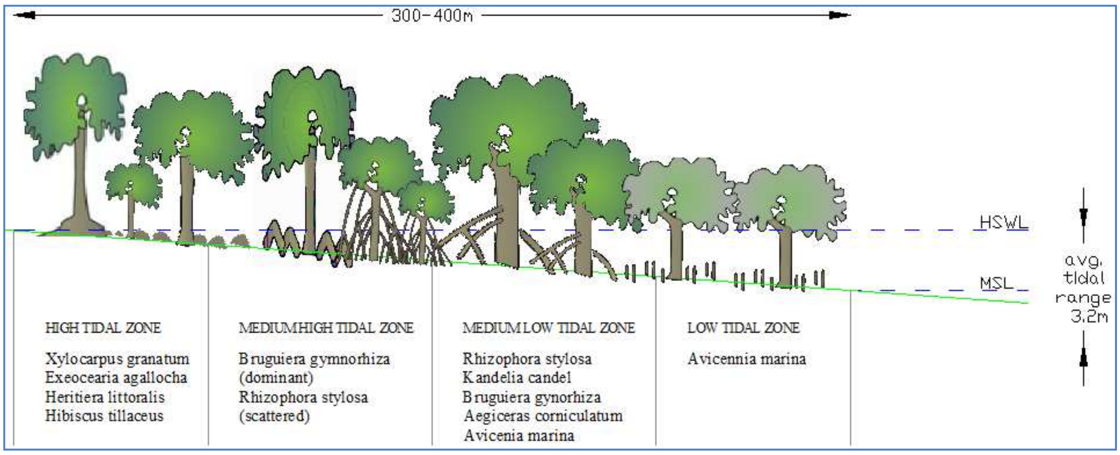

Figure 1. Mangrove zonation pattern at Chua Cape, Tien Yen district, Quang Ninh (Vietnam).

Each species have different physical parameters such as height, diameter of the roots and stems. Density of the vegetation also varies per species, furthermore each family of mangroves possesses characteristic attributes such as aerial or stilt roots. Mangrove areas are also characterized by mudflats that are present in front of the see side of a forest. Depending on tidal levels these flats vary in length and their slope is subjected to hydrodynamic conditions.

As may be expected, all these factors have a different influence on the extent of wave height attenuation. Therefore, at any given location where mangroves are present the wave reduction coefficient is different and their impact on coastal dike construction costs varies.

METHODOLOGY

Case Study Vietnam

The case study for the research [Tusinski, 2012] is the whole of coastline of Vietnam, where a number of coastal dikes were recently constructed and construction of many more is in the process or

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planning stage and thus cost data are available. Furthermore, Vietnam is one of the countries with an appropriate climate and suitable hydrodynamic conditions for the growth of mangroves. Data on physical parameters of mangroves, as well as met-ocean conditions were collected from the places located across whole length of the Vietnamese coastline- Hai Phong province in the North to Kien Giang province in the South.

Results from the case study on the wave height attenuation can be applied in other regions across the globe with similar vegetation, topographic and hydrodynamic conditions, which are contained in the ranges as presented in the Table 1 and Table 2.

Table 1. Range of input parameters analyzed in the research

Met-Ocean Conditions			Topographic Conditions	Physical Parameters of Mangroves	
Tidal Range	Storm Surge	Significant Wave Height	Slope of Mudflat	Spatial Density of Trunks	Trunk Diameter
1 – 4m	2 – 5m	2 – 7m	1:1000 – 1:2000	0.2 – 1.8 trunk/m^2	0.1 - 0.9m

A sensitivity analysis was carried out to investigate the influence of wave period and wind speed on attenuated wave height. The analysis showed that deviation of +/- 1s in wave peak period and +/- 5m/s in wind speed results in insignificant (order of 2%) increase or decrease of attenuated wave height as compared to base scenarios. The base case scenarios were analysed using wind/wave characteristics as presented in Table 2.

Table 2. Wave characteristics for typical average wind speeds during typhoon events

Wind Speed [m/s]	Significant Wave Height [m]	Peak Period [s]
13	2.0	6.0
15	3.0	7.0
18	4.0	8.0
22	5.0	9.0
25	6.0	10.0
28	7.0	10.5

Result from the case study on construction costs of a coastal dike shall be applied only for a location in Vietnam, as the cost data related to material, labour, equipment and land value were collected specifically from this country.

Computational Modelling

The computations were carried out using latest version of wave penetration model SWAN, in which the method of Schiereck and Booij (1996) to calculate the effect of wave energy dissipation in mangrove forest was implemented by Narayan, Suzuki (2010). The quality of modelling roots in numerical models like SWAN has been improved by a more detailed mathematical description of the root system on basis of photogrammetric method Bo (2012). Combining this with data from laboratory tests in Hannover Strusinska et.al (2013) leads to a good model description within SWAN.

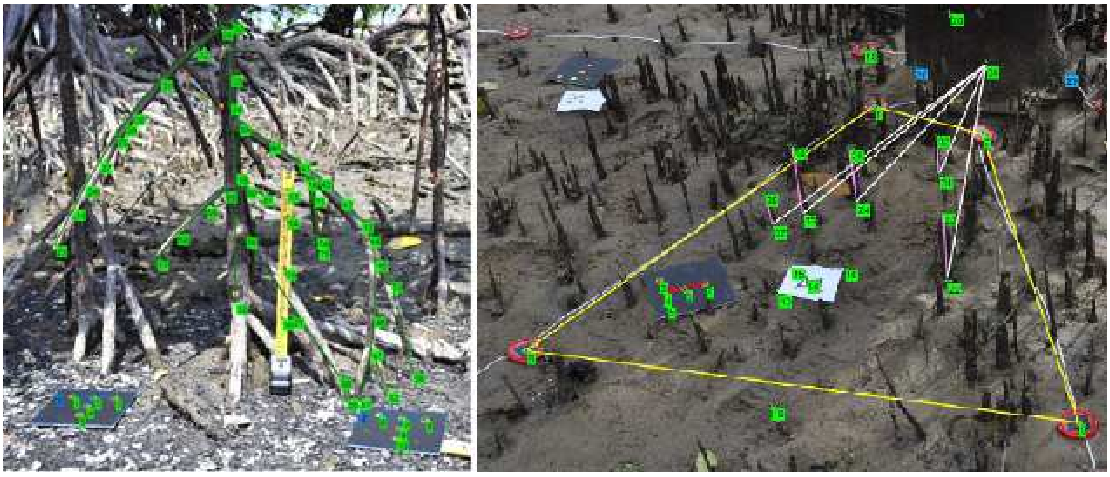


Figure 2. Photogrammetric triangulation to a prop-roots (left) and pneumatophores (right) [Bo, 2012].

Construction Costs Assessment

Cost data were gathered from the interviews made with the associates of different educational and governmental bodies in Vietnam, such as the “Center for Resource Consultancy and Technology Transfer” under the Ministry of Agriculture and Rural Development or Vietnam Water Resources University”. In-house cost database of “BMT Asia Pacific Pte Ltd” was also used to assess the labour and equipment costs of constructing the dike body.

Material costs are the average market prices dated in year 2012 based on several projects in two provinces: Nahm Dinh (rural) and Hai Phong (urban). From the data provided, it appears that the total costs of materials depend to large extent on their location; costs are higher in rural areas than in cities. That is the effect of the transportation costs that are included in the price. When the dike construction project is located in an urban area which is also an industry centre, the distance from the manufacturers that supply raw and fabricated materials is obviously shorter than in the case when the project is located in a further rural area. In this study, the location factor is omitted and the prices are averaged out, due to the fact that it does not contribute significantly to the total costs of dike construction.

As for the labour & equipment costs, similarly to the preceding case, the costs vary per project location. The labour cost displays an opposite relation; namely it is lower in rural areas. Here, these differences were also insignificant to the total costs of dike construction therefore the average value was used. From the data gathered on the mangrove restoration projects in Southern Vietnam (Ca Mau province) it appears that these costs also vary per location. In this case however the specific site and soil conditions play an important role. As it is widely known, the mangrove forests are rather difficult to establish artificially, due to their sensitivity and vulnerability to the varying environmental conditions. In the extreme cases when the trees are in their early growth stage, they need to be protected from the extreme water levels that reach their canopy and decrease their area of oxygen collection. Therefore small breakwaters need to be constructed offshore; this construction is included in the planting costs. In such cases, these costs can reach up to 3100 Euro/ha of mangrove vegetation. On the other hand, when no extra protection is necessary, the average costs oscillate around 540 Euro/ha. The cost of planting mangroves does not contribute significantly to the total costs of dike construction, therefore only one, the most expensive case was considered.

The coastal land value is another aspect rather difficult to establish and unify in one number. The function of the land, whether it is agricultural, residential or commercial is the governing factor here. In most of the cases, the land belongs to the government and its purchase is thus not a part of the cost estimate. However, it is worth noticing the value that the given land represents when not used for a flood defence structure. Such an analysis was carried out for agricultural land utilized for rice cultivation, the most common crop in Vietnam. The value of the land was estimated based on the average annual profit made during three harvesting periods per one hectare of land. This value was discounted over a period of 30 years with an average and estimated inflation rate of 5%. Value of the land calculated in this way allows assessing its real actual price, excluding the speculation which is a result of negotiations between government and the farmers, during which farmers usually ask for a price exceeding many times the land’s real value.

RESULTS OF THE ANALYSIS

Introduction

The coastline in front of mangroves consists of shallow mudflats with varying slopes and length, depending on the tidal amplitude. The initial run with the wave model was carried out to investigate the governing factors contributing to wave energy dissipation in the mangrove and mudflat zones.

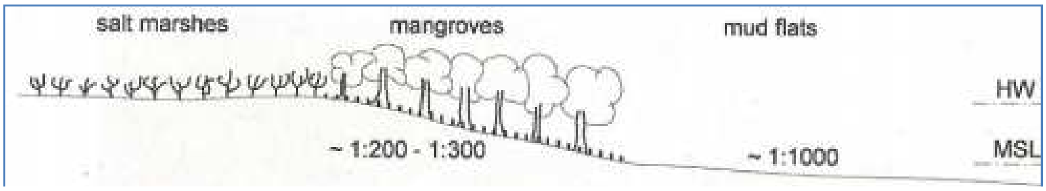


Figure 3. Cross section coast with mangroves.

From the result of the initial run (Figure 4) it can be clearly seen that in the mudflat zone (distance: 600-2100m), the governing wave damping factor is the depth. Bottom friction contributes very little to the total dissipated energy. The white-capping process is only present in the near shore zone (distance: 0-600m) and even then, does not significantly contribute to the wave decay. On the other hand, all three processes do not play any role in the mangrove zone (distance: 2100-2500m), and the wave energy is dissipated entirely due to the drag exerted on the encountered waves by the mangrove trunks.

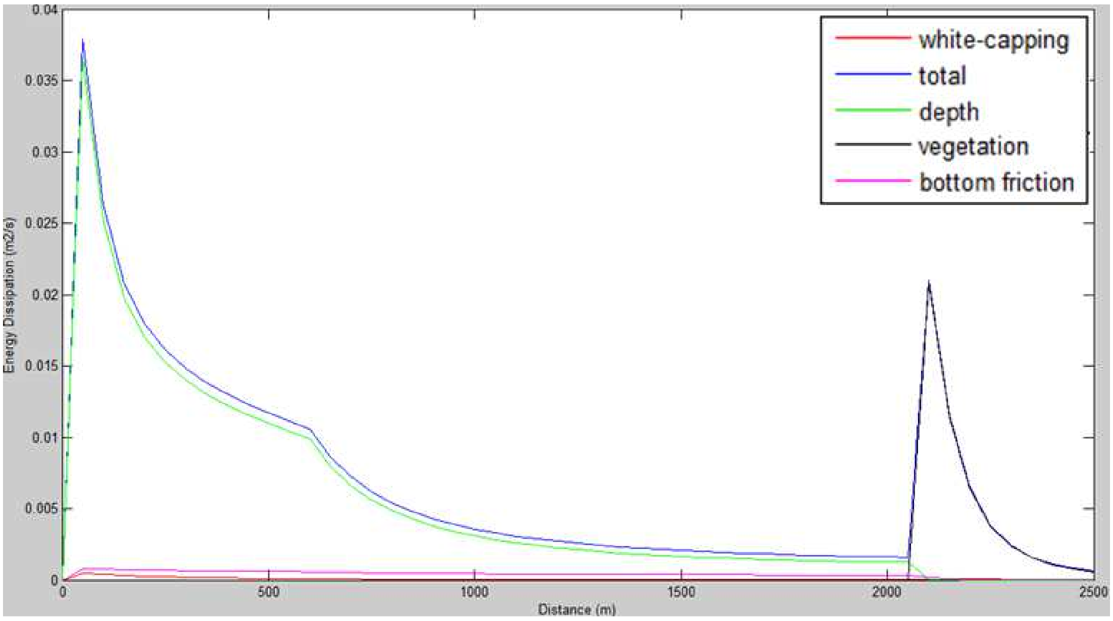
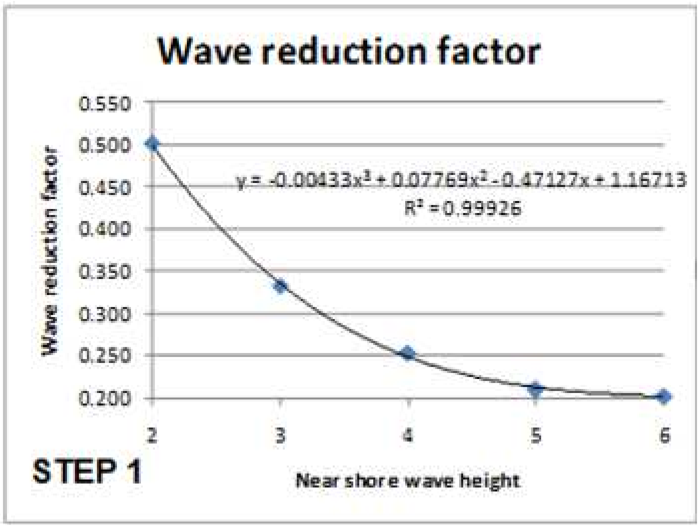


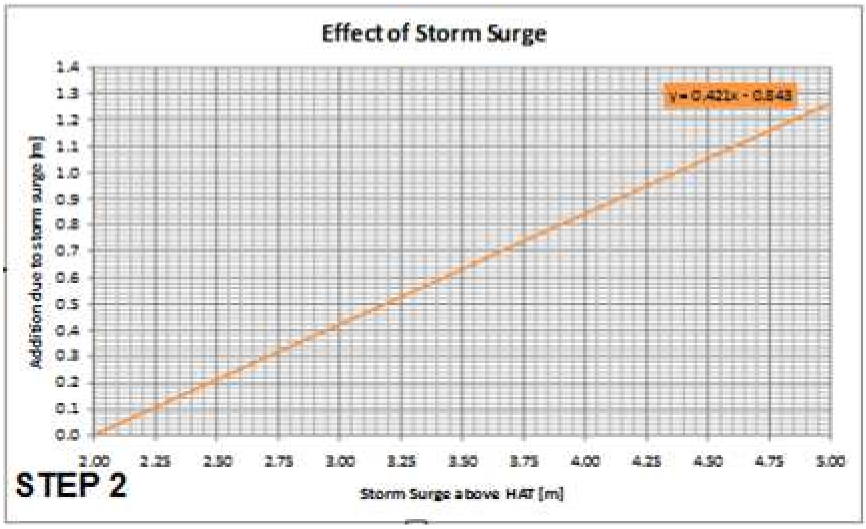
Figure 4. Result of the initial run – factors contributing to the wave energy dissipation.

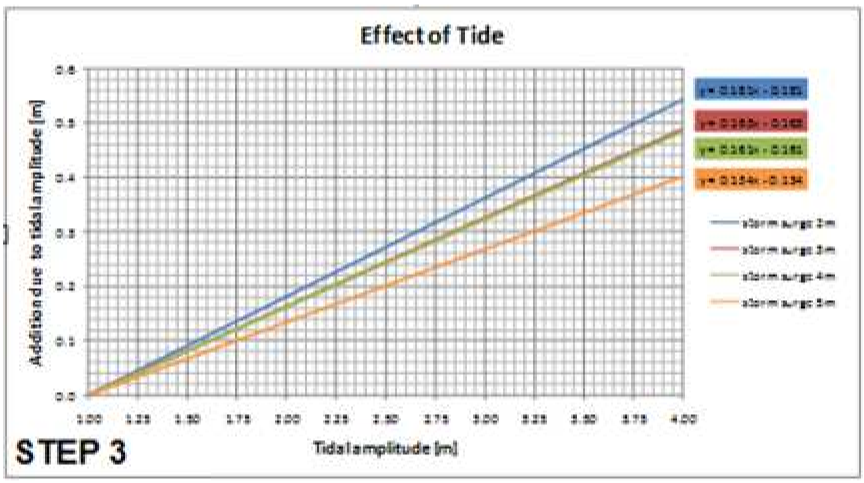
This finding allows investigating the wave height reduction in the zone specified above, by its division into two areas: mudflats – where the varying slope, storm surge and tidal amplitude will affect the ratio of wave reduction and the mangrove area. The governing physical parameters in the mangrove zone will be the height of the trees, their spatial density, diameter of roots and trunks or ratio of submergence of a tree.

Wave Dissipation in the Mudflat Zone

The design flow charts presented below allows estimating the attenuated wave height at the end of the mudflats depending on the given input parameters such as near-shore wave height, tidal range, storm surge level and slope of the sea bottom. The flow charts are valid for the combination of parameters given in Tables 1 and 2, except for a combination where $H_s < 3$m and storm surge level > 4m. For this combination of two parameters, the relation between near shore and attenuated wave height changes due to lesser impact of the bottom on the propagating wave.


Wave reduction factor
$y = -0.00433x^3 + 0.07769x^2 - 0.47127x + 1.16713$
$R^2 = 0.99926$
Wave reduction factor
0.550
0.500
0.450
0.400
0.350
0.300
0.250
0.200
2
3
4
5
6
STEP 1
Near shore wave height


Effect of Storm Surge
y = 0.421x - 0.843
Addition due to storm surge [m]
Storm Surge above HAT [m]
STEP 2


Effect of Tide
Addition due to tidal amplitude [m]
Tidal amplitude [m]
STEP 3

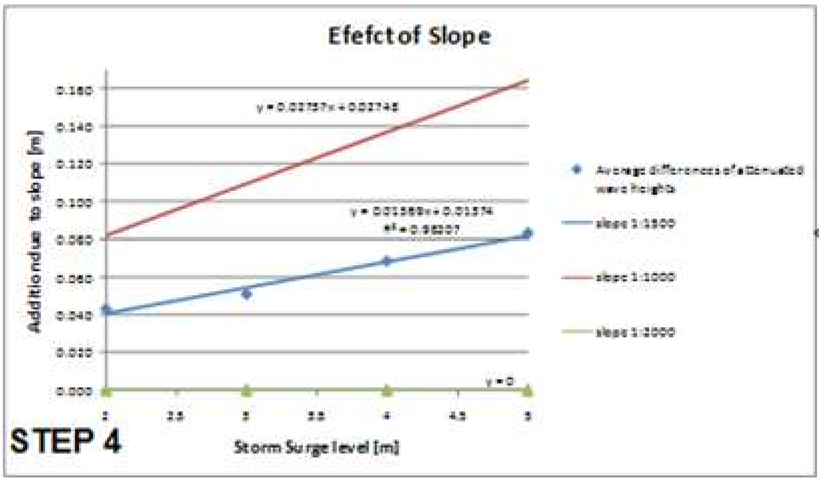


Figure 5. The design flow charts.

Example of calculations:

At a given location, the following data is available: near-shore wave height of 3.3m, storm surge of 3m, tidal amplitude of 2.75 and a slope of mudflats of 1:1500.

Following the flow charts it means that the wave reduction factor is 0.300, so the reduced wave height is 0.3 x 3.3 = 1.0m. Storm surge gives a surcharge of 0.42m, the tide gives a surcharge of 0.28m and the slope a surcharge of 0.05m. The total wave height at the end of the mudflat is: 1.0m + 0.42m + 0.28 + 0.05m = 1.75m

Wave Dissipation in the Mangrove Vegetation Zone

A total number of 135 simulation runs with varying parameters is carried out in order to investigate impact of them on wave height decay in the mangrove zone. The result was then a subject of statistical analysis. Presented below formulas is the result of non-linear curve fitting of equations into the data sets. The equations approximate simulated results with the accuracy of 0.02 - 0.15m (standard error of deviation).

1. CANOPY:

- Emergent Canopy:

$$K_{ce50} = exp(-2.014 + 0.003(C.C.)^3 + 1.252 ln(H_{ini})) \quad (1)$$

$$H_{att} = H_{ini} - \frac{K_{ce50}}{50} V.L. \quad (2)$$

- Submerged Canopy:

$$K_{cs50} = exp\left(-6.874 + \frac{0.635(\frac{H}{h})}{ln(\frac{H}{h})} + 1.783 ln(H_{ini})\right) \quad (3)$$

$$H_{att} = H_{ini} - \frac{K_{cs50}}{50} V.L. \quad (4)$$

Where:

K_{ce50} = wave height reduction factor for 50m of emergent canopy [m]

K_{cs50} = wave height reduction factor for 50m of submerged canopy [m]

H_{att} = attenuated wave height [m]

H_{ini} = initial wave height [m] – (range of validity: Hini = 0.5 – 3.0 m)

V.L. = vegetation length [m] – (range of validity: V.L. = 1– 200 m)

H/h = ratio of submergence [-] – (range of validity: H/h = 1.25 – 2)

H = water depth [m]

h = height of a tree [m]

C.C. = canopy coefficient [-]

C.C. = 1 , for lower part of a canopy

C.C. = 2 , for upper part of a canopy

C.C. = 4 , for fully submerged canopy (H/h = 1)

2. TRUNKS:

- Initial wave height = 3m:

$$K_{t50-3} = 0.571 + 0.118ln(Den) + 0.136ln(Diam) \tag{5}$$

$$H_{att} = H_{ini} - \frac{K_{t50-3}}{50} V.L. \tag{6}$$

- Initial wave height = 2m:

$$K_{t50-2} = 0.365 + 0.074ln(Den) + 0.096ln(Diam) \tag{7}$$

$$H_{att} = H_{ini} - \frac{K_{t50-2}}{50} V.L. \tag{8}$$

- Initial wave height = 1m:

$$K_{t50-1} = \exp\big(-1.78 + 0.505l\,n(Den) + 0.539ln(Diam)\big) \tag{9}$$

$$H_{att} = H_{ini} - \frac{K_{t50-1}}{50} V.L. \tag{10}$$

Where:

K_{t50-3} = wave height reduction factor of 3m wave, for 50m of trunks [m]

K_{t50-2} = wave height reduction factor of 2m wave, for 50m of trunks [m]

K_{t50-1} = wave height reduction factor of 1m wave, for 50m of trunks [m]

H_{att} = attenuated wave height [m]

H_{ini} = initial wave height [m] – (range of validity: Hini = 0.5 – 3.0 m)

V.L. = vegetation length [m] – (range of validity: V.L. = 1 – 200 m)

Den = Spatial density of trunks [trunk/m2] – (range of validity: Den = 0.2 – 1.8 trunk/m2)

Diam = Diameter of trunk [m] – (range of validity: Diam = 0.1 – 0.9 m)

In case of intermediate values of the initial wave height (Hini) e.g. 2.5m, the wave height transmission factor can be obtained by calculating attenuated wave height for K_{t50-3} and K_{t50-2} and interpolating linearly the obtained values. The linear interpolation between obtained values is possible due to fact that the values calculated with the equations 5, 7 and 9 appear to display the linear relationship between each other, as can be deducted from the visual inspection of the their graphs presented in Figure 6. The linear interpolation, therefore allows calculating the K_{t50-x} values with reasonable accuracy.

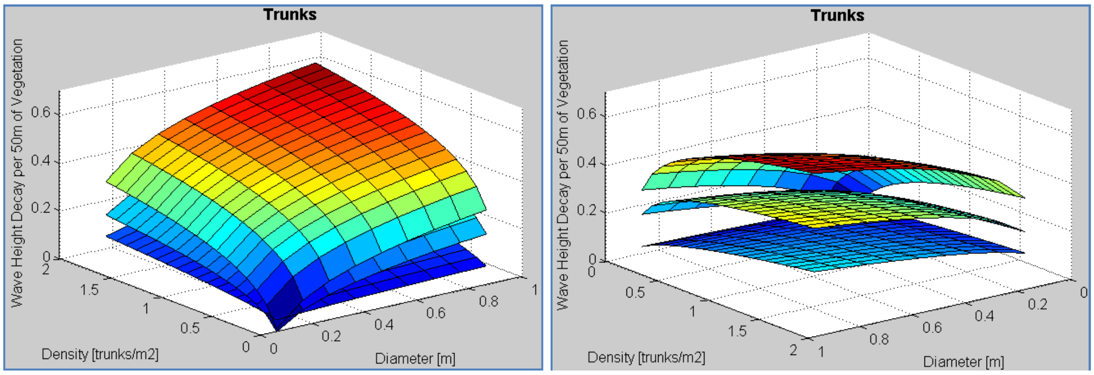


Figure 6. Equations 5, 7 and 9 plotted in one coordinate system. Right figure presents the results plotted on the coordinate system rotated with 180° around z-axis as compared to the figure on the left.

3. PROP ROOTS:

$$K_{pr50} = \exp\left(-1.788 - \frac{2.359}{\sqrt{(Den)}} + 1.386\ln(H_{ini})\right) \tag{11}$$

$$H_{att} = H_{ini} - \frac{K_{pr50}}{50} V.L. \tag{12}$$

Where:

K_{pr50} = wave height reduction for 50m of prop roots [m]

H_{att} = attenuated wave height [m]

H_{in}i = initial wave height [m] – (range of validity: Hini = 0.5 – 3.0 m)

V.L. = vegetation length [m] – (range of validity: V.L. = 1 – 200 m)

Den = Spatial density of prop roots [root/m2] – (range of validity: Den = 2 – 10 trunk/m2)

4. UNVEGATATED CASE:

The analysis of the wave height attenuation in the unvegetated case was conducted for two main reasons. Firstly, in order to obtain the wave reduction coefficients (Kr) by comparing attenuated wave height in each of the vegetation scenarios to the one obtained in the unvegetated case. This analysis was made for the scenarios with a bottom slope of 1:200.

- Initial wave height = 3m:

$$K_{unv50-3} = 0.072 + 0.007(S.S.) + \frac{1.661}{(T.R.)} - 0.008(S.S.)^2 - \frac{0.45}{(T.R.)^2} - 0.157\frac{(S.S.)}{(T.R.)} \tag{13}$$

$$H_{att} = H_{ini} - \frac{K_{unv50-3}}{50} V.L. \tag{14}$$

- Initial wave height = 2m:

$$K_{unv50-2} = -0.013 + 0.026(S.S.) + \frac{0.729}{(T.R.)} - 0.005(S.S.)^2 - 0.141\frac{(S.S.)}{(T.R.)} \tag{15}$$

$$H_{att} = H_{ini} - \frac{K_{unv50-2}}{50} V.L. \tag{16}$$

- Initial wave height = 1m:

$$K_{unv50-1} = \left(741.1 - \frac{1025.4}{\sqrt{(S.S.)}} + 3.17(T.R.)^2\right)^{-1} \tag{17}$$

$$H_{att} = H_{ini} - \frac{K_{unv50-1}}{50} V.L. \quad (18)$$

Where:

$K_{unv50-3}$ = wave height reduction factor of 3m wave [m]

$K_{unv50-2}$ = wave height reduction factor of 2m wave [m]

$K_{unv50-1}$ = wave height reduction factor of 1m wave [m]

H_{att} = attenuated wave height [m]

H_{ini} = initial wave height [m] – (range of validity: Hini = 0.5 – 3.0 m)

V.L. = Mudlfat length [m] – (range of validity: V.L. = 1 – 400 m)

T.R. =Tidal range [m] – (range of validity: T.R. = 1.0 – 4.0 m)

S.S. = Storm surge [m] – (range of validity: T.R. = 2.0 – 5.0 m)

As in the case of wave height decay due to effect of trunks, the wave height transmission factor for the intermediate values of H_{ini}, can be calculated by the linear approximation of two nearest values of $K_{unv50-x}$. This interpolation is however less accurate as in the case of trunks, especially for the higher values of storm surge, and tidal range and lower values of H_{ini}, where the water depth has very little effect on the wave height decay.

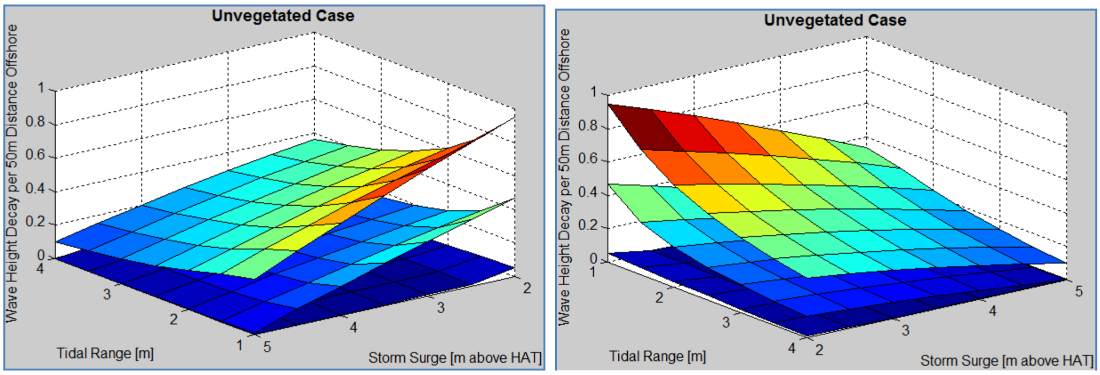


Figure 7. Equations 13, 15 and 17 plotted in one coordinate system. Right figure presents the results plotted on the coordinate system rotated with 180° around z-axis as compared to the figure on the left.

REDUCTION OF COSTS OF A COASTAL DIKE CONSTRUCTION

Wave height reduction results directly in two aspects of a coastal dike construction, that is: the lowering of the crest level due to smaller wave run up height and lighter revetment structure due smaller force acting on the protection structure.

The wave run up height can be calculated using the “old Delft formula”, which is valid for the wave not exceeding the Iribarren number of ξ=3.0. That means that the formula can be applied for the waves considered in this study (wave height of 0.5m and period not exceeding 7s, wave height of 3m and period not exceeding 10m). For the dike outer slope of 1:4 this means that the run up height is always twice as big as the wave height. This implies that a wave height reduction of 1 meter results in the construction of 2 meters of lower dike. For both of the considered cases of the protection structure (grass and concrete blocks), the value of the surface roughness reduction factor can be assumed to be 1. Thickness of the stable placed-block revetment can be calculated using Pilarczyk formula (1990). For the given dike geometry and wave conditions, the block thickness varies from 0.3 to 0.5m for the wave heights of 0.5 to 2m respectively. Smaller wave heights result in smaller wave loads on a structure. For that reason the soft solution for the revetment structure was also considered in the cost analysis. The test conducted in Delta flume of Delft Hydraulics, as well as field tests with the overtopping simulator in Vietnam (Trung, 2014) proved the efficiency of a uniform closed-cover grass with high density roots such as e.g. Vetiver as a revetment for sea dikes. Waves of 0.75m, even during a 24 hours storm showed no damage to the grass-covered layer. Waves of 1.4m damage started after approximately 6 hours, but even then the hole in the dike body increased very slowly. As presented in all of the 4 analyzed cases in section 4.3 the grass layer used as a revetment can be successfully utilized when the wave damping system of mangrove trees exists in front of a dike, and sometimes, when the water levels are low, even without it.

Figure 8 presents the total costs of dike construction with a crest level ranging from 2-10m which are typical dike heights in Vietnam. Two cases were considered: one with no mangroves and concrete blocks used for the revetment and the second with mangrove forest in front of a dike with grass layer revetment. From the figure below it can be deducted that three factors have marginal influence on the total dike construction costs that is value of the land, planting of mangrove forest (400m wide, incl. construction of a low breakwater) and the reinforced grass. Cost of each of these factors is around 100 000 Euro per one kilometer of a dike with a height ranging from 2-10m. Construction of a dike body and placed block revetment considerably contributes to the total cost. As a result costs of a softer solution including grass and mangroves are approximately twice as low as the cost of a typical dike unprotected by mangroves with concrete blocks used as the revetment.

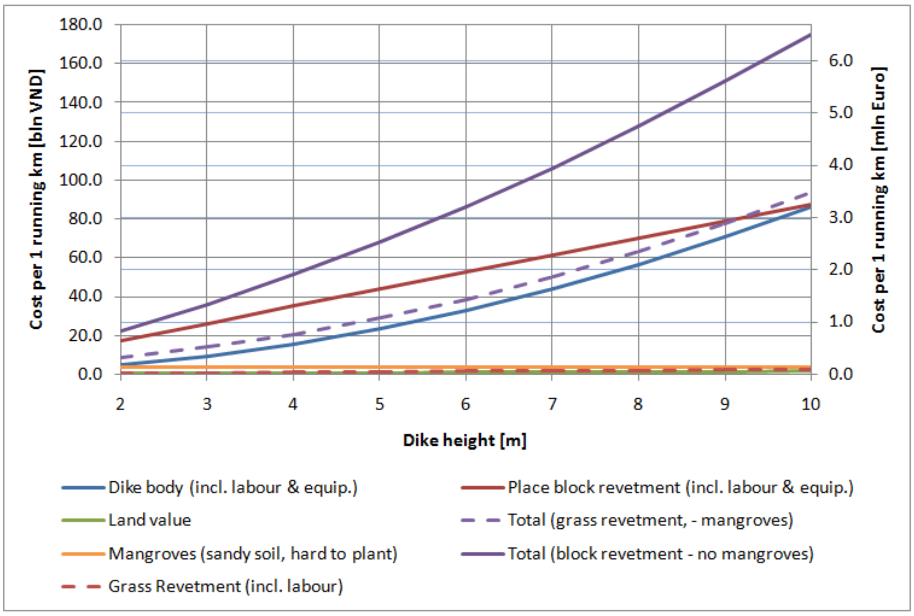


Figure 8. Costs of 1 running kilometre of a dike.

Based on the assumptions made in the preceding sections, the cost reduction of a coastal dike construction as a function of a wave height decay and crest height can be calculated (Figure 9). The cost obtained using the figure below, are the savings made by reducing the design wave height by the mangrove vegetation as compared to the original, unprotected by mangroves design with a hard revetment. In both cases the toe of the dike is situated at the mean high water level (MHWL) and the revetment covers whole outer slope from the toe up to crest level.

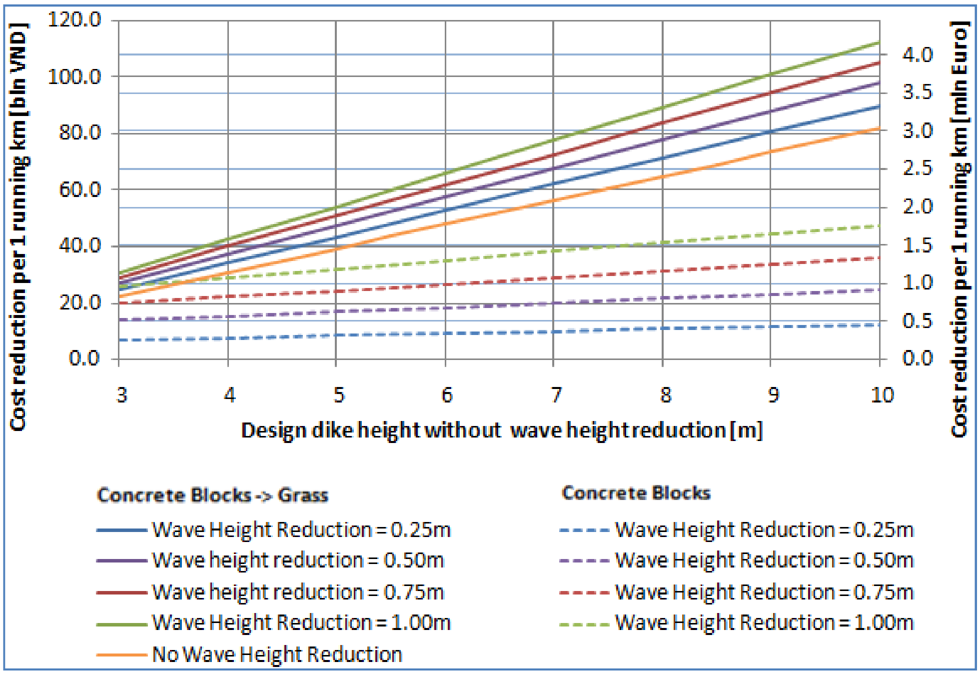


Figure 9. Reduction of dike costs as a function of wave height reduction.

For a typical dike in Vietnam with a crest level of +6m MHWL, the total construction cost reduction due to 0.5m wave height attenuation equals to 0.7mln Euro per running kilometer of a dike. This is consistent with the previous study of Hillen (2008) and Mai (2008). In the same case when the grass-cover is applied this cost, spikes up to about 2.2mln euro. These savings increase to a value of c.a. 0.9mln euro and 3.7mln euro (for the above case respectively) when the design dike is 10m high.

CONCLUSION AND RECOMMENDATIONS

Conclusions

The analysis made in this study showed that the costs of a coastal dike construction in Vietnam can be effectively reduced by incorporating mangrove vegetation in the design. The extent of this reduction is subjected to the vegetation pattern, which is a function of various parameters i.e. growth stage of the trees, length of the forest, as well as the met-ocean conditions such as tidal amplitudes and storm surge levels. As it was presented, a 0.25m reduction in wave height leads to the total savings of around 0.25mln Euro per one running kilometer of a 3m high dike, when utilizing a hard revetment. If 0.25m wave height reduction results in the possibility of applying soft revetment such as the Vetiver grass, these savings dramatically increase to the value of 0.9mln Euro per kilometer of a dike. These construction cost savings can already be achieved by planting 200m mangrove vegetation, where the sparsely distributed mangrove trunks (0.2-0.6 unit/m2) of varying diameters from 0.2 to 0.7m will be the elements obstructing wave propagation. Hydrodynamic simulations have proven that the emergent mangrove canopy is the most effective in attenuating wave height. In such scenarios, when the water levels are higher, the 400m long mangrove patch reduces wave height up to 0.70m. As a result, the cost of constructing 1km of a 6m high dike, can be reduced up to 1mln and 2.3mln Euro in cases where concrete blocks or reinforced grass are used respectively.

The design of a coastal dike is made for the extreme events that are characterized by high water levels. Incorporating mangroves in this design should therefore be made in such a way to maximize the wave height reduction effect. If the site's specific, design water levels are known, the appropriate species chosen for plantation should be chosen in such a way that the water level during extreme events would be able to reach lower or upper part of a canopy. That implies that even relatively young and short trees can be considered as a wave damping system when the design water levels are relatively low. High water levels considered during the design, disparage the role of roots as the wave damping system. Prop roots of a mature tree of *Rhizophora* or *Sonneratia* usually reach about 2m above the bottom level. However design water levels are rarely that low. The same applies for the buttress roots of landward, red mangrove species. The effect of knee roots or pneumatophores, due to its height (max.20-30cm) is negligible and can be omitted during the design of coastal dikes.

Based on this study, the following conclusions regarding the analyzed topics can be drawn:

MUDFLAT ZONE:
- The governing process affecting wave energy dissipation in the mudflat zone is the depth induced wave breaking,
- Of the three parameters: storm surge, tidal range and bottom slope gradient, only the first two contribute significantly to the wave energy dissipation,
- A steeper slope causes more energy dissipation due to the effect of shoaling. However in the mudflat zone, the steeper slope equates to its shorter length, as it is defined by the tidal amplitudes. Therefore in cases the waves have less time and space to dissipate their energy and therefore are higher as compared to cases with gentler slopes and longer mudflat lengths. Furthermore, gentle slopes (1:1000 – 1:2000) cause no shoaling effect,
- The wave period and wind speed have marginal effects on wave energy dissipation.

MANGROVE ZONE:
- The most effective segments of a mangrove tree in wave energy dissipation are the emergent canopy, followed by roots, trunks and submerged canopy,
- The effect of roots, in the majority of cases can be neglected due to the fact that during extreme events, the water levels exceed the height of root systems such as pneumatophores, buttress knee roots and even prop roots,
- The submerged canopy has a negligible effect on the wave energy dissipation when the ratio of submergence (H/h) exceeds 1.5,
- The magnitude of wave energy dissipation due to mangrove trunks is dependent on the trunk diameter and spatial density. Among these two parameters the trunk diameter has a larger influence,
- The length of the vegetation contributes to the wave energy dissipation. The longer the vegetation patch, the smaller the wave height at the end of the mangrove zone. The majority of the wave energy is dissipated within the first 100 to 200m of the vegetation patch,
- When the wave breaker index Hs/hd >0.4, the scarce vegetation is not the only factor contributing to the wave energy dissipation. In such cases the dissipation is a result of the coupled effect of water depth and vegetation. This effect is valid only for scarcely populated and short mangrove trees, when the trunks and submerged canopy respectively, (ratio of submergence H/h>1.5) cause the wave energy dissipation.

COSTS OF A COASTAL DIKE:
- Costs of the dike body and placed block revetment are the most significant amongst the others that contribute to the total cost,
- Value of agricultural land, planting mangrove and grass revetment have marginal contribution to the total cost,
- Wave height reduction of 0.5m leads to the total cost savings from 0.5-0.9mln Euro on 1km dike construction for 3 and 10 meter high dike respectively, when the concrete block revetment is used,
- When 0.5m wave height reduction, allows using soft revetment such as reinforced grass, these savings increase to about 1.0-3.3mln Euro per 1km of a dike.

Recommendations

The formulas derived in this study yield two types of errors: an error due to reliability of the computational model and an error due to approximation. Reliability of the computation can be improved by calibrating the wave breaking index for the wave computations in the mudflat and the drag coefficient in the mangrove zone. The nature of this research, wave attenuation during extreme events, makes the calibration with the field measurements virtually impossible. In order to obtain the results from the field, the measurements would have to be obtained during extreme events (high water levels and wave heights). Validation of the wave heights obtained in this study could be however made for some of the scenarios with lower water levels and wave heights by adjusting the breaker index, for the case of the mudflat zone. Validation of the approximated wave heights in the mangrove zone, from the same reason as above should not be based on the field measurements. Small scale physical models may be helpful in this case. Scaling down a mangrove tree, preserving its physical features (e.g. flexibility) can be troublesome especially in case of the canopy. The physical modeling should therefore be made carefully. Obtained results can be compared to the computed ones, and in case of discrepancy the drag coefficient in the computational model should be modified.

The construction costs of a coastal dike in Vietnam are approximated rather accurately. Due to variance of these costs per region and a specific type of an area, the approximation of the costs for generic purposes yields a certain inaccuracy. This influence is considered however to be marginal. The factor that is believed to contribute more significantly to the material costs is the distance from the supplier to the site. In case of remote sites, the transport costs can be relatively high. This matter is advised to be investigated more in detail. As for the land value obtained in this study, it applies only to agricultural land and dikes constructed in rural areas. Some segments of dikes in Vietnam are however built in the industrial or touristic regions and therefore land value will certainly differ and is believed to be higher.

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