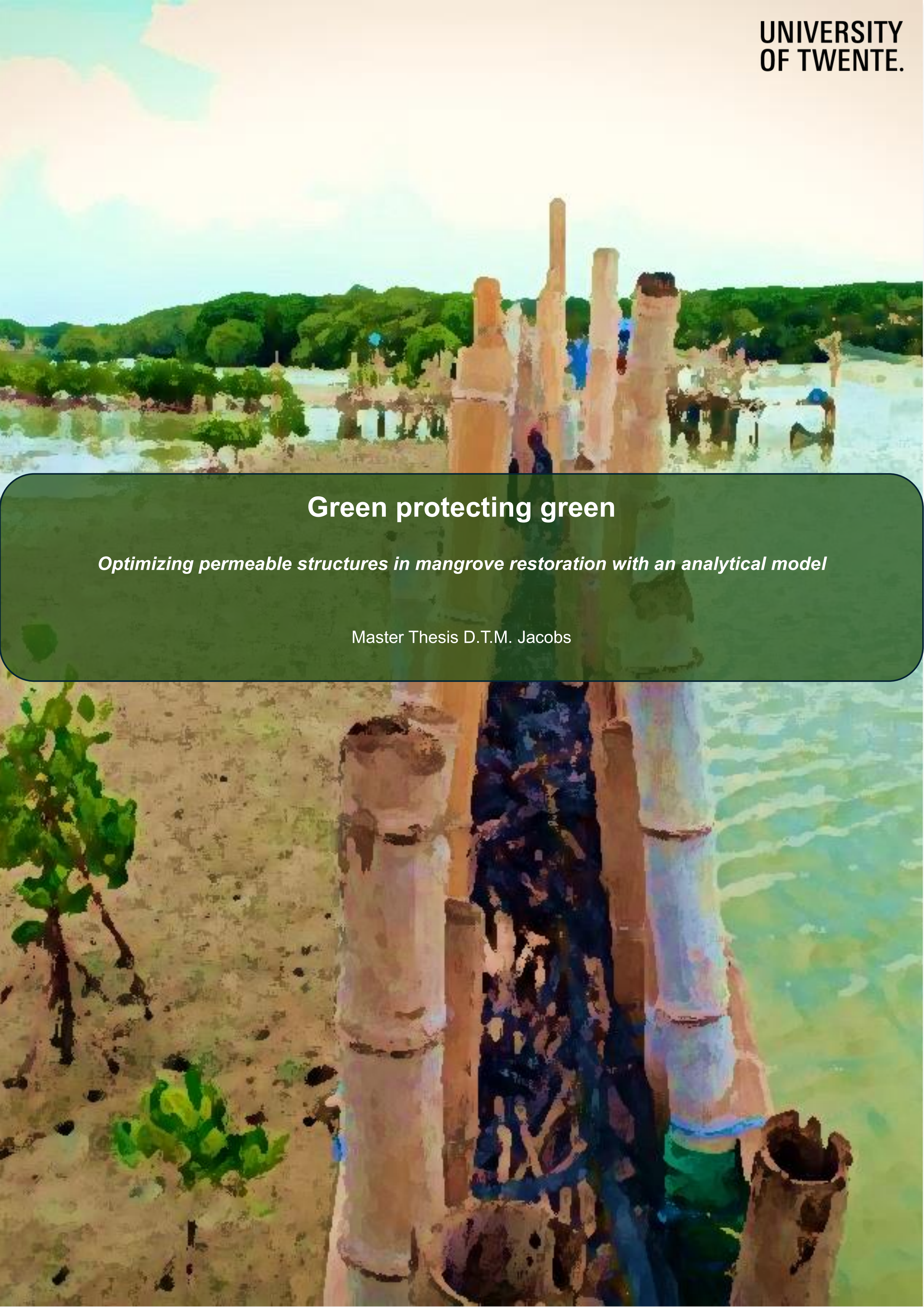

UNIVERSITY OF TWENTE.

Green protecting green

Optimizing permeable structures in mangrove restoration with an analytical model

Master Thesis D.T.M. Jacobs

Master Thesis
Green protecting green:

Optimizing permeable structures in mangrove restoration with an analytical model

By

D.T.M. Jacobs

To obtain the degree of Master of Science at University of Twente, to be defended publicly on the 3rd of July 2025 at 13.45 hours

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Preface

I thoroughly enjoyed my student days at the University of Twente in Enschede, but all good things must come to an end. With the completion of this master's thesis, the 'school' chapter in my life comes to a closure. A new chapter, work, will be written. With that, I will enter a period with new fun challenges, opportunities, and developments.

I have enjoyed broadening myself over the past few months by developing and owning knowledge in ocean wave propagation. Seeing progress and getting a better understanding of the processes taking place always gave me immense satisfaction. I am therefore proud of the report you are currently reading.

I would like to thank Witteveen+Bos and my colleagues there for their trust in me, offering me this interesting study and all the help I have received in recent months. A special thanks goes to Tom Wilms. He guided the process throughout the master thesis and I was always able to ask questions. Another Witteveen+Bos colleague I would like to thank in particular is Gert Klopman. He always succeeded in helping to keep things sharp. He was also always there for me for math checks.
I would like to thank not only my colleagues at Witteveen+Bos, but also Rutger Siemes for our 2 weekly meetings and guidance during the graduation process. I would also like to thank Erik Horstman for his guidance during key moments in the process.

Besides those involved in this research, I would also like to thank my family and friends. They have provided me with support, relaxation, and tips over the past few months. I would also like to thank my current employer for giving me space during my studies, especially during the thesis process. A special thank you to my parents for always being there for me and giving me perseverance. To be completely honest, hadn't expected to finish a master's degree after getting meningitis. Yet here I am now facing the possibility of doing so anyway. In addition, I would like to thank my grandfather. Without his genes, I probably would not have entered this field and would have had a harder time standing my ground as a woman in the field (of civil engineering). Nevertheless, his work will live on in the work I will make. I hope he is watching with humble pride.

Dimphy Jacobs

26th of June 2025
Siebengewald

Abstract

In previous decades, there has been a global reduction of mangrove areas due to human influences. To bring back some of the lost mangroves, mangrove restoration projects are being implemented. A frequently used method to do so is the use of permeable dams. This method is also used in the Demak Region in Indonesia.

The main objective of this research is to determine to what extent the design of permeable structures used in mangrove restoration projects can be optimized using a model that computes the depth-variable wave energy transmission of different design options. The 'optimal' dam design depends on limited material usage and a minimum transmitted wave energy.

An analytical model is developed that calculates the depth-variable wave energy in the water column and the total wave energy. The developed model focuses on intermediate wave conditions. This way, it is observed at what water depths the wave energy should be 'dissipated' to meet the maximum energy that allows for mangrove development. Furthermore, horizontal elements are simulated in the model. These represent the permeable structures, represented as horizontal bamboo beams attached to vertical bamboo poles. Four design options with varying placement of the horizontal elements relative to the water level are simulated. For each design option, the wave energy reflection, wave energy dissipation, and the resulting transmitted wave height are examined. The horizontal elements are represented with dissipation, reflection, and transmission coefficients. The maximum wave energy that mangrove seedlings at various ages and for all hydrodynamic conditions can withstand is calculated. This is called the 'critical wave energy'. It is examined which of the design options reduces the wave height that does not exceed the critical wave energy. The model gives good guidance in choosing and analyzing the implementation of different design options. It is easy to conclude which design option is the most efficient one. At last, the model output is used to determine the optimal design. The Design option where a gap between the seabed and the last horizontal element increases is considered to be the optimal design option. A specific design with specified placements of the horizontal elements is, however, not advised, since it is condition and site-specific. Finally, expert elicitation clarifies the practical applicability of the model in the field. The expert elicitation clarified the practical applicability of such a model in the field. It also helped determine the risks of assumptions and simplifications made. It is recommended to conduct a stability analysis of the structure in further research. Furthermore, it is recommended to implement morphodynamic and socio-economic processes into the model and the design phase.

Key words: *Analytical model; Bamboo structure; Building with nature; Drag coefficient; Mangroves; Permeable; Wave energy dissipation; Wave energy reflection; Wave energy transmission*

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List of symbols

Symbol	Unit	Description
A	m^2	Cross-section wave flume
A_c	m^2	Flow area between cylinders
C_D	-	Bulk drag coefficient
$\widetilde{C_D}$	-	Depth-averaged drag coefficient
$C_{D,w}$	-	Empirical drag coefficient related to wave dissipation rate
c_w c	s^{-1}	Wave propagation velocity
E_d	W	Energy dissipation
E_K	W	Kinetic energy
E_P	W	Potential energy
E_r	W	Reflected wave energy
E_T	J/m^2	Total energy
E_t	J/m^2	Transmitted wave energy
E_∞	J/m^2	Total energy of incoming waves
η	m	Water surface displacement
g	m/s	Acceleration due to gravity
h	m	Water depth
H_s	m	Significant wave height of incoming waves
$H_{s,t}$	m	Significant wave height of transmitted waves
K_d	-	Damping coefficient
K_r	-	Reflection coefficient
K_t	-	Transmission coefficient
L	m	Wave length
π	-	Ratio of a circle's circumference to its diameter
ρ	kg/m^3	Water density
σ	s^{-1}	Wave angular frequency
T	s	Wave period
u	m/s	Undisturbed velocity
u_c	m/s	Drag velocity
u_s	m/s	Horizontal velocity under wave under shallow water waves conditions
$\hat{u}_s$	m/s	Horizontal orbital velocity amplitude under shallow water conditions
u_i	m/s	Horizontal velocity under wave under intermediate water waves conditions
$\hat{u}_i$	m/s	Horizontal orbital velocity amplitude under intermediate water conditions
z_b	m	Bed elevation level
ζ	m	wave elevation

1. Introduction

Mangroves can offer protection against waves, erosion, and storm surges (Dahdouh-Guebas et al., 2005; Del Valle et al., 2020; Gedan et al., 2011; Gijón Mancheño, 2022; Knol et al., 2010; Montgomery et al., 2018; Quartel et al., 2007; Temmerman et al., 2023). It is also known that the roots of mangroves have the ability to dissipate waves and currents, trap sediments, and reduce the erosion of sediments (Brunier et al., 2019; Gijón Mancheño, 2022; Montgomery et al., 2018; Temmerman et al., 2023). Mangroves are also able to keep up with Sea Level Rise (SLR) (Gedan et al., 2011). Figure 1 shows the process of sediment deposition, wave attenuation, and soil reinforcement by mangroves.

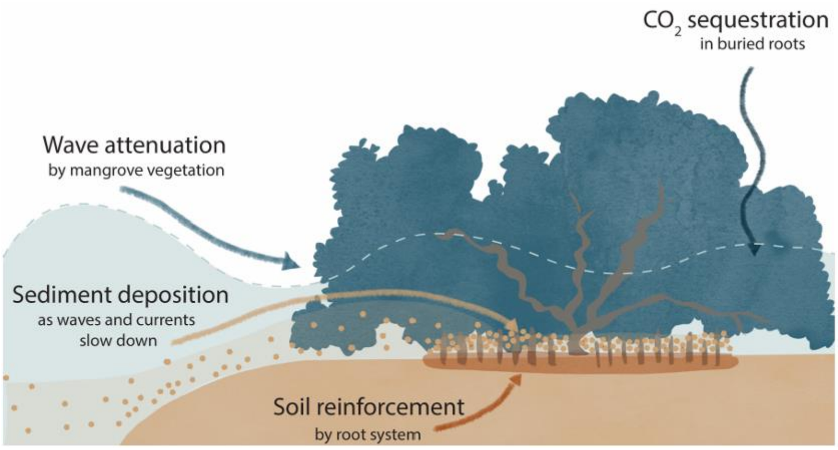

Figure 1 Sediment deposition, wave attenuation, and soil reinforcement by mangroves (Gijón Mancheño, 2022)

Mangrove forests are found around the globe in tropical and subtropical climates (See Figure 2). One of the areas where mangrove forests can be found is Indonesia. However, in previous decades there has been a reduction of mangrove areas due to human influences (Gijón Mancheño et al., 2021a; Valiela et al., 2001). Globally, there has been a reduction of mangrove forests of around 39 percent since the eighties (Valiela et al., 2001). The main human drivers of the deforestation of mangrove forests are: population growth, aquaculture, agriculture, wood productions, and infrastructure (Defries et al., 2010; Valiela et al., 2001; J. C. Winterwerp et al., 2020). Due to the building of aquaculture ponds, mangroves are being cut down and the coast will be excavated. If the ponds are deteriorated or abandoned causes larger water depths and the propagation of bigger waves. Therefore, the coast will get eroded even more, and the bed will get less stable because the roots no longer stabilize the sediments (Gijón Mancheño, 2022). The effect of building aquaculture ponds on coastal retreat is shown in Figure 3.

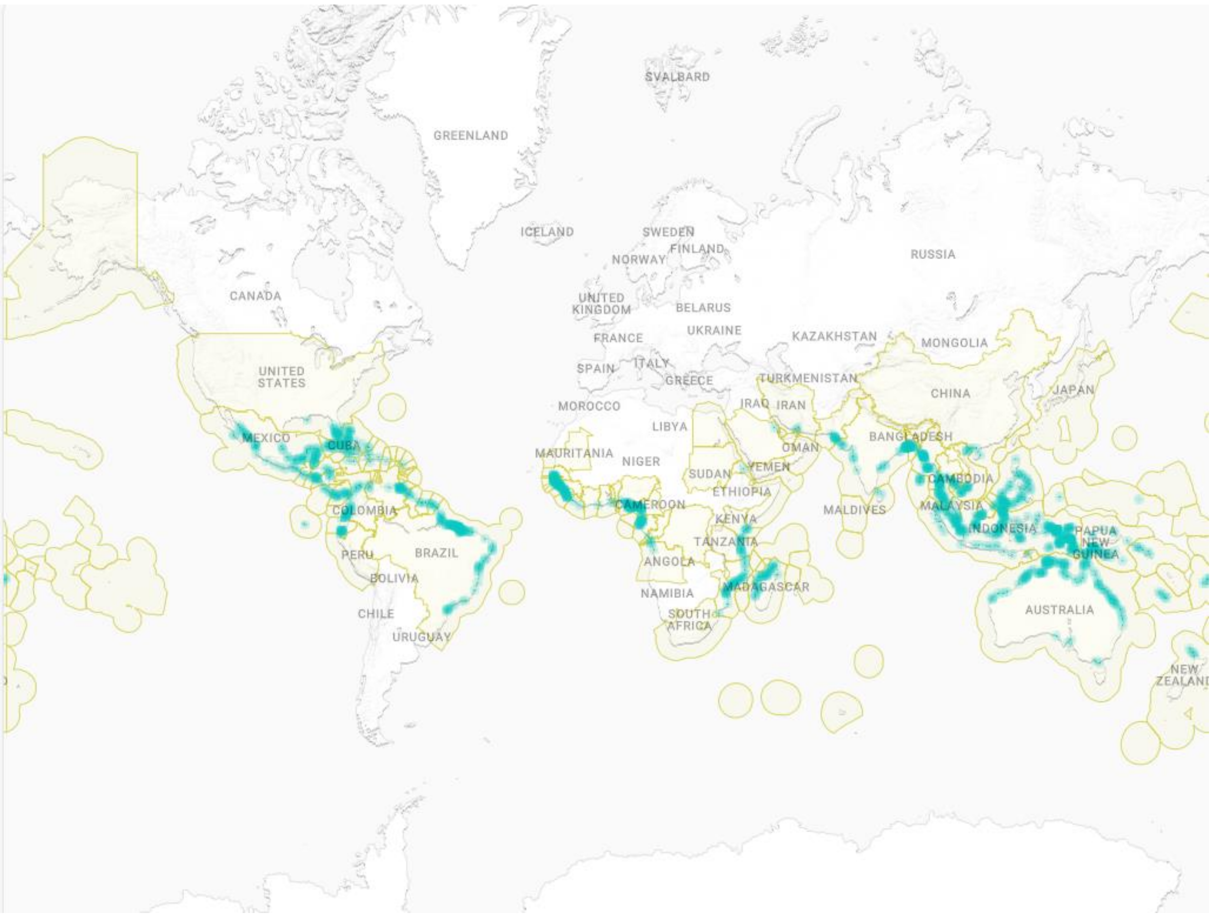

Figure 2: Mangroves around the globe (Global Mangrove Watch, n.d.)

However, in previous decades there has been a reduction of mangrove areas due to human influences (Gijón Mancheño et al., 2021a; Valiela et al., 2001). Globally, there has been a reduction of mangrove forests of around 39 percent since the eighties (Valiela et al., 2001). The main human drivers of the deforestation of mangrove forests are: population growth, aquaculture, agriculture, wood productions, and infrastructure (Defries et al., 2010; Valiela et al., 2001; J. C. Winterwerp et al., 2020). Due to e.g. the building of aquaculture ponds, mangroves are being cut down and the coast will be excavated. This causes larger water depths and the propagation of bigger waves. Therefore, the coast will get eroded even more and the bed will get less stable due to the removed roots (Gijón Mancheño, 2022). The effect of building aquaculture ponds on coastal retreat is shown in Figure 3.

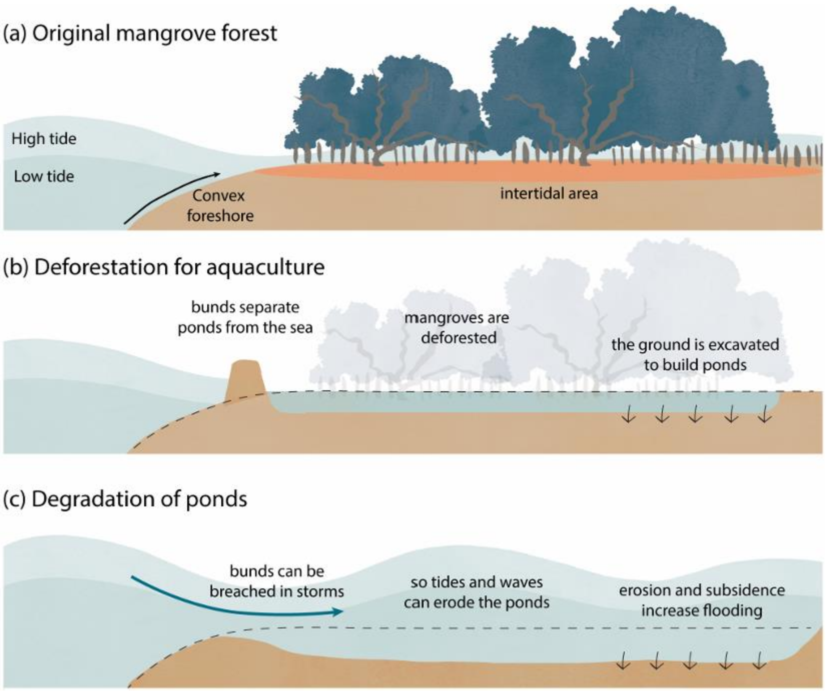

Figure 3: How aquaculture deforests mangroves and causes erosion (Gijón Mancheño, 2022)

To make mangrove restoration possible, there must be more sediment deposition than erosion.

The construction of permeable structures can help reduce the flow, wave height, wave energy, turbulence and reflect, dissipate, or transmit attenuated waves (Tonneijck et al., 2015; Wilms et al., 2020; J. C. Winterwerp et al., 2020). This results in calm water conditions behind the permeable structure. These conditions allow sediments to settle and the net sediment balance to restore, which can help mangroves to establish again (Wilms et al., 2020; J. C. Winterwerp et al., 2020). These calm conditions furthermore provide an area for saplings to grow and recover, where they will not get flushed away (Tonneijck et al., 2015). Figure 4 shows how permeable structures can contribute to mangrove restoration by creating conditions that are beneficial for mangroves to grow and maintain.

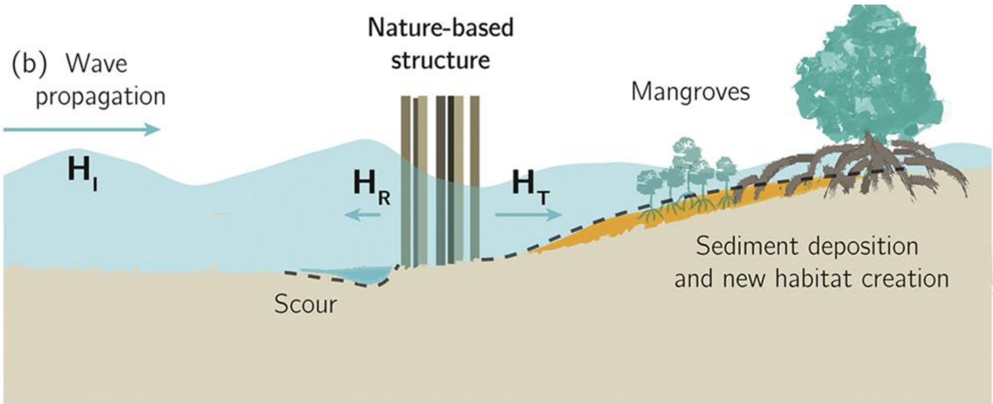

Figure 4: Wave attenuation and sediment deposition in case of a permeable dam (Gijón Mancheño et al., 2021a)

In this report, Chapter 2 contains the research context. This chapter gives an overview of the existing literature that is related to the research topic. Furthermore, the knowledge gap is introduced, as well as the scope and research questions of this research. Chapter 3 describes the research methodology. The results are shown in Chapters 4 and 5. A discussion of the gathered results is given in Chapter 6. Finally, Chapter 7 describes the conclusions of this research. Recommendations for further research are given in Chapter 8. There are 8 appendices attached to the research.

2. Research Context

2.1. Mangrove hydrodynamics

2.1.1. Wave characteristics

Linear (airy) wave theory

Linear wave theory assumes that wave heights are small compared to their length and the water depth. Linear wave theory applies when

$$H/L \ll 1 \qquad and \qquad H/h \ll 1 \qquad (1)$$

(Dean & Dalrymple, 1991; The Open University, 1999; Van Der Werf, 2024). According to linear wave theory, a 2D-progressive wave can be represented as a sinusoidal wave, see Figure 5.

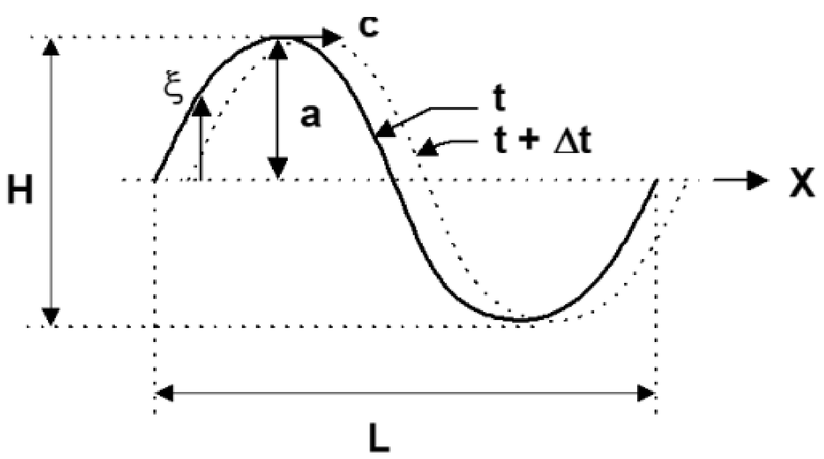

Figure 5: sinusoidal wave according to linear wave theory with wave height H [m], wave length L [m], phase velocity denoted as c in the figure but notated as c_w in the equations (Van Der Werf, 2024)

Following e.g. (Dean & Dalrymple, 1991; The Open University, 1999; Van Der Werf, 2024).The wave amplitude can be calculated using Equation 2

$$a = 1/2 * H \qquad (2)$$

The wavelength is expressed as L [m], the wave period is expressed as T [s] and the wave propagation velocity is expressed as $c_w = L/T$. The elevation of the water level ζ [m] is calculated using Equation 3

$$\zeta\,(x,t) = a * sin(\sigma t - kx) \qquad (3)$$

where σ [s^{-1}] represents the angular wave frequency and $\sigma = 2\pi/T$. Parameter k [m^{-1}] represents the wave number as $k = 2\pi/L$ (Dean & Dalrymple, 1991; Van Der Werf, 2024). This means that the wave propagation velocity can be notated as $c_w = \sigma/k$ [s^{-1}].

Following the dispersion relation (Equation 4),

$$\sigma^2 = gk \tanh(kh) \quad (4)$$

$$c_w = \sqrt{g/k \tanh(kh)} \quad (5)$$

the wavelength increases with the water depth and wave period (Van Der Werf, 2024).

According to (Dean & Dalrymple, 1991; The Open University, 1999; Van Der Werf, 2024). The incoming wave energy of a linear wave is proportional to the wave height squared and can be calculated using Equation 6

$$E = 1/8 * \rho * g * H^2 \quad (6)$$

Where, E [J/m^2] represents the total incoming wave energy.

Wave breaking

When waves are too steep, they will break. The maximum wave steepness is calculated using Equation 7

$$(H/L)_{max} = 0.14 * \tanh(kh) \quad (7)$$

2.1.2. Water particle movements

Orbital water movements are unaffected by the bed in deep water. Orbital movement reduces with depth and is negligible from about half the wavelength. In intermediate and shallow water depths, the orbital movement gradually flattens (Figure 6) (The Open University, 1999).

2.1.3. Shallow, intermediate, and deep water conditions

In oceans, one might speak of shallow water wave conditions, intermediate wave conditions, and deep water wave conditions. The conditions have different characteristics. These characteristics are listed in the table below and visualized in Figure 6. If the water depth-to-wave length ratio is smaller than 1/20, shallow water conditions apply. For a water depth-to-wave length ratio between 1/20 and ½, intermediate wave conditions apply. Deep wave conditions apply as soon as the water depth-to-wave length ratio is bigger than 0.50.(Dean & Dalrymple, 1991; The Open University, 1999; Van Der Werf, 2024)

According to Dean & Dalrymple (1991), The Open University (1999), and Van Der Werf (2024), the orbital movement of water particles under shallow water conditions have an elliptical shape. As the water particle moves closer to the seabed, the height of the ellipse decreases. Under shallow water conditions, the vertical orbital velocities and forces can be neglected. This is also shown in Figure 6.

Dean & Dalrymple (1991), The Open University (1999), and Van Der Werf (2024) also state that in intermediate water conditions, the orbital movement of water particles transitions between an ellipsoidal and a circular shape (Figure 6). As water particles are located closer to the seabed, the height of the shapes decreases (Figure 6).

For deep water conditions, the orbital movements of the water particles have the shape of a circle. Again, as water particles are located closer to the seabed, the diameter decreases. This is also shown in Figure 6.

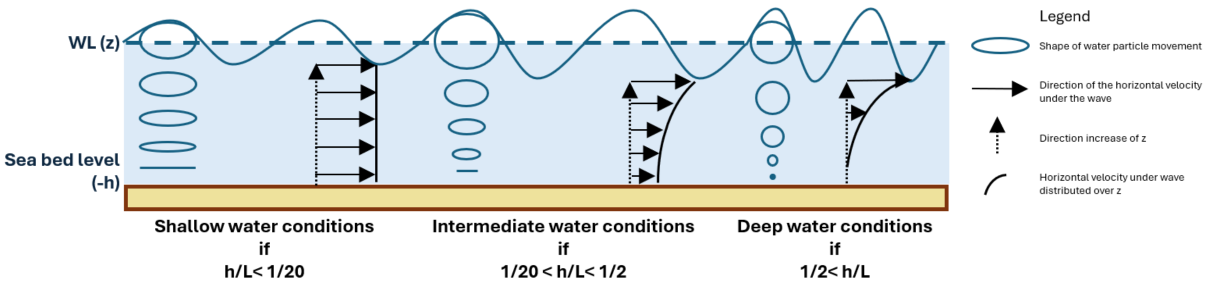

Figure 6: Orbital particle movements and velocities under shallow, intermediate, and deep water conditions

2.2. Propagules establishment

2.2.1.Propagule establishment

The rehabilitation of mangrove forests relies on the dispersal and development of propagules. These are predecessors of the seedlings. Seedlings are propagules that have settled and already started growing. (Thillaigovindarasu, 2023). After being dispersed from the parent tree, propagules strand or float for a species-specific period before settling as the tide recedes. This allows them to establish (Thillaigovindarasu, 2023). Key thresholds for propagule establishment include an inundation-free period for rapid root development and sufficient root length to resist hydrodynamic forces (Balke et al., 2011; Thillaigovindarasu, 2023). Furthermore, longer roots for survival against erosion and dislodgement during high-energy events (Balke et al., 2011; Thillaigovindarasu, 2023). Van Bijsterveldt et al. (2022) identified opportunities to overcome establishment challenges, such as limited propagule availability and reducing hydrodynamics through methods like permeable dams, though these are effective mainly in non-subsiding areas.

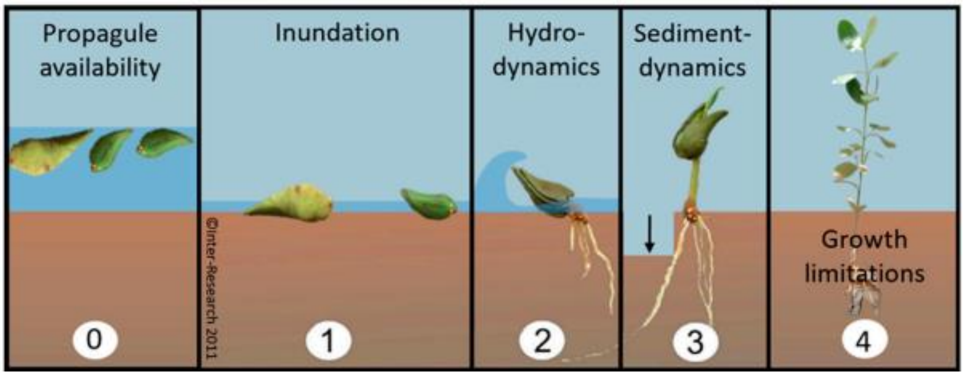

Figure 7: Windows of opportunity for mangrove propagule development (van Bijsterveldt et al., 2022)

2.2.2. Maximum resistible bed shear stresses and erosion

Accordingly to Balke et al. (2015), for a mangrove propagule, there is a maximum critical erosion depth and bed shear stress that a seedling is able to resist. How the maximum resistible bed shear stress can be calculated is described in the methodology. Using the critical bed shear stress, the maximum wave energy a mangrove seedling can resist can be calculated. This is also explained in the methodology.

Tides, currents, and waves significantly impact seedling establishment. Tides induce cross-shore currents, aiding sediment transport and propagule dispersal (Bisschop, 2023; Pritchard et al., 2002). Weak residual currents and currents caused by waves have minimal impact on sedimentation or erosion (Smits, 2016; Thillaigovindarasu, 2023). Typically, waves contribute more to bed shear stress than currents, especially in shallow waters, influencing sediment transport patterns (Bisschop, 2023). During storm seasons, significant sediment erosion and accretion are expected. Understanding these dynamics is crucial for effective mangrove forest rehabilitation. Furthermore, it is known that small waves erode sediment, whereas large waves both supply and erode sediments (Bisschop, 2023; J. C. Winterwerp et al., 2013). Tides bring in sediments (Bisschop, 2023; J. C. Winterwerp et al., 2013). The influence of waves and tides on sediment transport is also shown in Figure 8. During the storm season, most of the sediment erosion and accretion is expected to occur (Bisschop, 2023; J. C. Winterwerp et al., 2020).

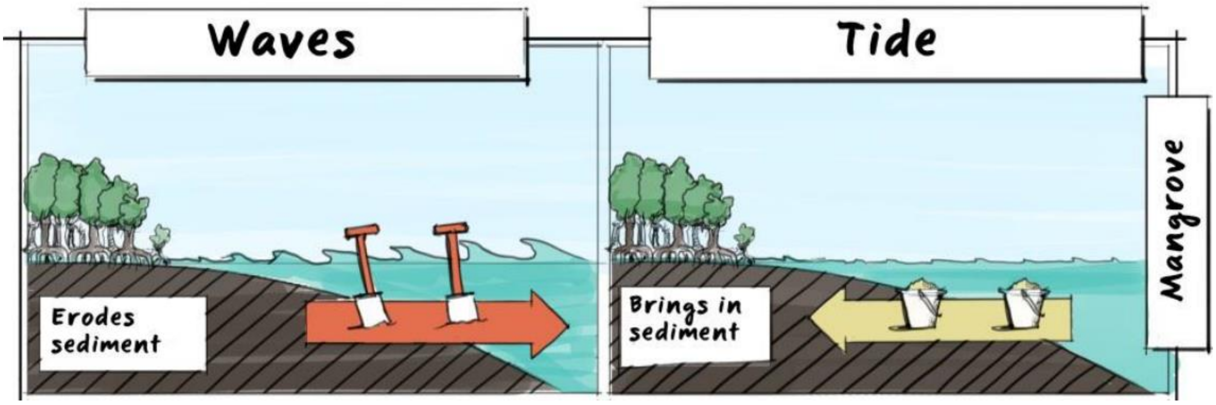

Figure 8: Visualisation of the impact of waves and tide on sediment transport (H. Winterwerp et al., 2014)

2.3. (Permeable) structures used in mangrove restoration projects

In mangrove restoration projects, different designs for permeable structures are used. Common materials that are used are: wood, bamboo and brushwood (Amrit et al., 2021; Wilms et al., 2020; J. C. Winterwerp et al., 2020). Frequently used designs consist of bamboo or PVC poles with a brushwood filling, vertical bamboo poles, horizontal bamboo beams attached to vertical PVC or bamboo poles, and wooden fences (Amrit et al., 2021; Gijón Mancheño et al., 2025; Wilms et al., 2020; J. C. Winterwerp et al., 2020).

Figure 9 Design options for permeable structures. A) Vertical bamboo poles. B) Vertical bamboo poles with a brushwood filling. C) Wooden fence with vertical bamboo poles and horizontal bamboo plates. D) Vertical bamboo poles with horizontal bamboo beams.(Gijón Mancheño et al., 2025; Wilms et al., 2020; J. C. Winterwerp et al., 2020)

Existing literature has issued guidelines on the different dimensions, material choices, implementation guidelines, and the positioning of the dams (Wilms et al., 2020; J. C. Winterwerp et al., 2020). The existing design methods and guidelines are based on expert judgement. The values mentioned in Wilms et al. (2020) and J. C. Winterwerp et al. (2020) are also not variable or tested using different hydrodynamic conditions. The mentioned design guidelines are described in Appendix A.

Furthermore, it is mentioned that bamboo poles should have a carpet protection layer and that the fill material should consist of brushwood branches (Wilms et al., 2020; J. C. Winterwerp et al., 2020). However, the brushwood filling can be easily damaged and lose its function (Wilms et al., 2020; J. C. Winterwerp et al., 2020).

2.4. Influence of vertical structures on wave propagation

Waves that propagate into a permeable structure are partly reflected E_r, dissipatedE_d, and transmitted E_t (J. C. Winterwerp et al., 2020). The wave energy of the incoming waves is partly dissipated, reducing the wave height behind the structure. (see Figure 10). The exact relation between the optimization of the dam design to reach a maximum drag coefficient while using the minimum amount of material is not well known(J. C. Winterwerp et al., 2020).

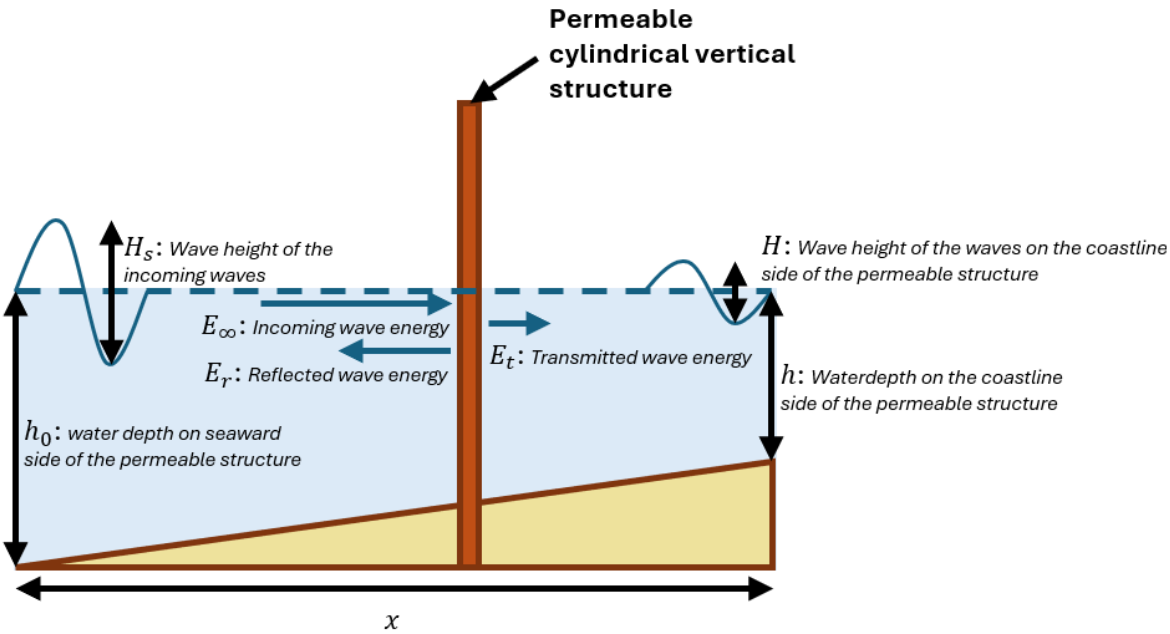

Figure 10: The influence of a permeable structure on wave propagation

2.5. Modelling the effect of wave attenuating structures

Various types of models have already used in previous research to assess the impact of vertical (permeable, cylindrical) structures on wave propagation. These models include numerical options such as SWASH, SWAN, CFD-based tools, and Delft3D (Bisschop, n.d.; Dao et al., 2021; Hadadpour et al., 2019; Kumar et al., 2021; Mendez & Losada, 2004; Mussert, n.d., 2024; Spröer et al., 2024; Suzuki et al., 2019; Thillaigovindarasu, 2023; Vuik et al., 2016). SWAN models are based on depth-averaged conditions. SWASH and 3D models (such as CFD and Delft3D) are time-consuming. Time-consuming models are less suitable for performing numerous calculations in the search for an optimum. For calculations that require depth-specific data, an analytical approach is preferable. Mainly because of its time efficiency. However, this kind of model does not account for longshore effects. This method is ideal for optimization purposes as it can quickly perform many calculations and is easy to use.

The choice of model depends on specific research objectives and the required level of complexity. Regardless of the model selected, it is crucial to have data on local hydrodynamic conditions and bathymetry available for input into the model.

2.6. Knowledge gaps

The current design guidelines for permeable structures used in mangrove restoration already guide in choosing parameters, dimensions, and materials in general. However, it lacks flexibility and adaptability to specific on-site conditions. Additionally, the values mentioned in Wilms et al. (2020) and J. C. Winterwerp et al. (2020) are not variable to local conditions or tested using different hydrodynamic conditions, and are purely based on expert judgement. Furthermore, Mussert (2024) mentions that it is not clear how varying hydrodynamic conditions affect the design variables and structure performance. One area has other (hydrological) conditions than another. A design method that incorporates the local conditions is missing. Such a method can indicate how material use can be minimized. It is not yet clear how much wave energy has to be lost to meet the conditions in which mangroves can establish themselves (J. C. Winterwerp et al., 2020). This can, however, be calculated using the shear stresses provided in Gijsman et al. (2024) and Balke et al. (2011). There is not yet a guideline or tool for optimizing the design of a permeable structure to attenuate the waves sufficiently.

A design for permeable vertical structures under varying hydrodynamic conditions could be optimized using an analytical model. Such a model helps to investigate which of the design options requires the least amount of material while still obtaining the maximum accepted transmitted wave height for mangrove restoration. There does not seem to be such a model yet. The structures that will be considered in this study will consist of vertical bamboo poles with horizontal bamboo plates attached to them. This is a relatively new structure in mangrove restoration projects (Gijón Mancheño et al., 2025).

2.7. Research objective

The objective of this research follows from the knowledge gaps. The main objective of this research is to determine to what extent the design of permeable structures used in mangrove restoration projects can be optimized using a model that computes the depth-variable wave energy transmission of different design options. The theory of Balke et al. (2011) is used for calculating the maximum allowed wave energy that mangrove seedlings can survive. To perform the research, the following research questions are formulated.

2.7.1. Research questions

The main research question of this Master Thesis is

To what extent can the design of permeable structures used in mangrove restoration projects be optimized using a model that computes the depth-variable wave energy transmission of different design options?

An answer to the main research question shall be found by answering the following sub-questions:

SQ1. How can the depth-variable wave energy in (inter)tidal areas for different wave conditions and water depths be quantified by an analytical wave model?

SQ2. How can the impact of different design options for permeable structures on the depth-variable wave energy be implemented into this model?

SQ3. What is the maximum wave energy that corresponds to the maximum bed shear stress that mangrove seedlings can survive?

SQ4. For which structure design options can mangrove restoration/establishment be achieved while minimizing the number of horizontal elements?

SQ5. What are, according to experts within the field, the limitations of the current design method and the benefits and applicability of a model?

SQ5.1 What are the limitations of the current design method?

SQ5.2 What are the limitations of using the in this thesis generated model for the design of permeable structures used for mangrove restoration?

SQ5.3 What factors/elements increase the likelihood of experts using the model for their research or design regarding permeable structures used for mangrove restoration projects?

2.8. Study area

2.8.1. Topography

This research focuses on the Demak coastal region, in the province of Central Java in Indonesia, which is shown in Figure 11. The coastal zone of Demak is located near the Java Sea. The coast consists of gentle muddy slopes of approximately 1:600 (Tonneijck et al., 2015).

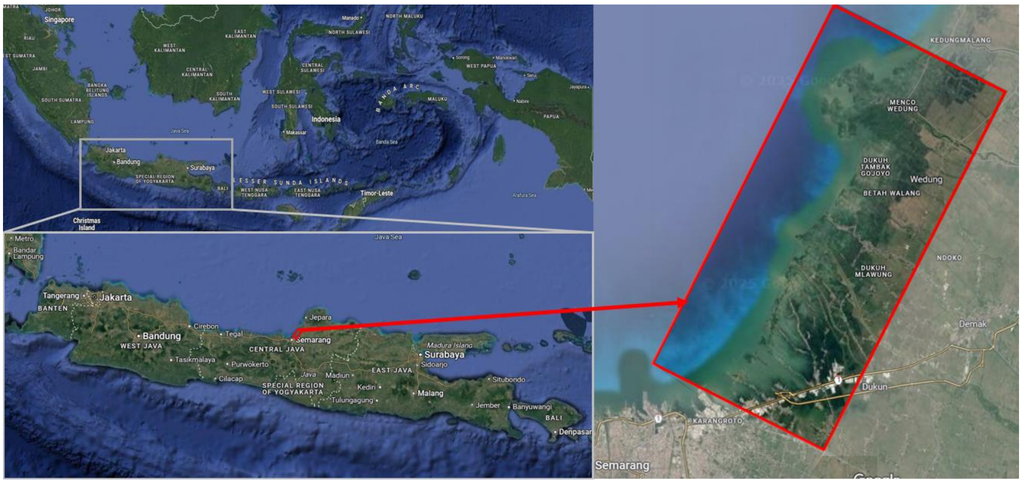

Figure 11: Study area

This area has a tropical climate with two monsoon seasons (Amrit et al., 2021). Between May and September, there is the South East (SE) monsoon. Between October and April, there is the North West (NW) monsoon (Amrit et al., 2021).

Over the years, the region has become more economically dependent on shrimp farming (Tonneijck et al., 2015). This has caused mangrove forests in the region to be converted into shrimp ponds (Tonneijck et al., 2015). At the same time, the coastal vulnerability has increased due to sea level rise and subsidence (Tonneijck et al., 2015).

2.8.2. Hydrodynamic conditions

In the area, the neap and spring-tidal ranges are 0.40 meters and 0.60 meters, respectively (Winterwerp et al., 2014). According to Tas et al. (2020), the S.E. monsoon season has calm wave conditions, whereas the N.W. monsoon season is the 'wet' season with higher wave conditions.

In this study, the values shown in Table 1 are taken into account for the hydrological parameters. It should be noted that the mean water depth is based on literature and measurements. The tidal range is based on the IHO data. The tidal range consists of Spring Low Tide (SLT), Mean Low Tide (MLT), Neap Low Tide, Mean Sea Level (MSL), Neap High Tide (NHT), Mean High Tide (MHT), Spring High Tide (SHT) and a storm condition. The wave heights and periods are based on the ERA 5 data. The stormwater depth is based on the literature.

Table 1: Hydrodynamic conditions used in the analytical wave model. Storm conditions are based on Alferink (n.d.). Wave depths are based on Tas et al. (2020)

parameter	Unit	SLT	MLT	NLT	MSL	NHT	MHT	SHT	Storm condition 10% occurrence
H_s	m	0.20, 0.50	0.20, 0.50	0.20, 0.50	0.20, 0.50	0.20,0.50	0.20, 0.50	0.20, 0.50, 1.20	0.20, 0.50, 1.20
T_p	s	3-5	3-5	3-5	3-5	3-5	3-5	3-5	3-5
h	m	0.17	0.27	0.40	0.50	0.60	0.72	0.87	1.91

It should be noted that only wave conditions that comply with the maximum wave steepness will be used to calculate the wave energy distribution. The complete determination of these conditions, are shown in Appendix C.

2.9. Research scope

An 1D-analytical model is created. This model is used to determine depth-varying wave energy, and how it propagates through structures. The simulated structures consist out of horizontal bamboo plates attached to bamboo poles that are standing vertically in the seabed. These horizontal elements are represented as a reflection coefficient of 1. It should be noted that only wave characteristics over the determined tidal range are modeled. A visualization of the permeable structure that is simulated in the model, is shown in Figure 4. The model represents a case in the Demak Region in Indonesia. Morphological processes are not considered within the research. Nor will the stability of the structure itself.

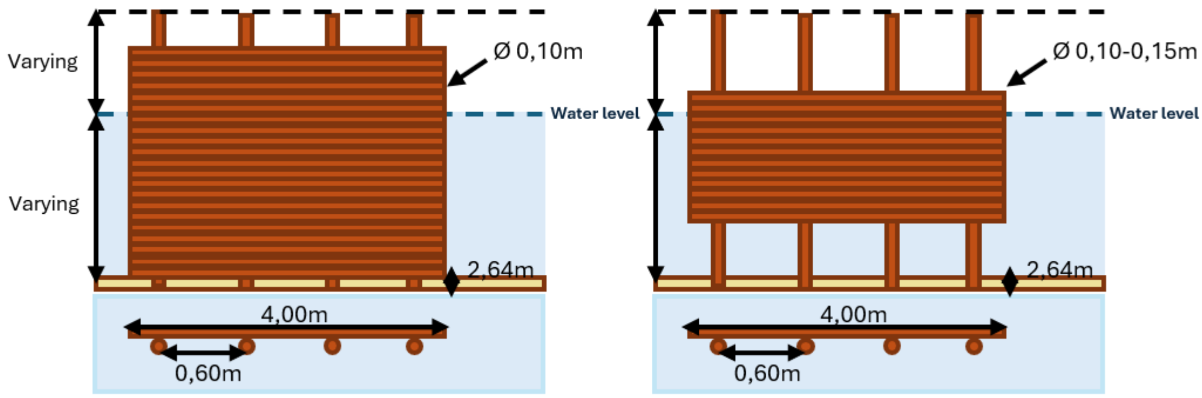

Figure 12: Sketch of permeable structure that will be implemented into the analytical (wave) model

Furthermore, some simplifications are made. These are listed in Table 2.

Table 2: Assumptions and simplifications made in this research versus the reality

Model	Reality
Only waves occur	Waves and currents could occur together
Only regular waves	Irregular waves occur
Linear wave theory applies	Not only linear wave theory applies
Waves only approach perpendicular to the structure	Waves approach under different angles
No sediment transport is taken into account	Sediment transport occurs
Even seabed	No even seabed
Stability of the structure is not taken into account	Structure could be not stable
Only horizontal elements are considered	Both horizontal as vertical bamboo elements are used

3. Methodology

The research starts by finding an answer to the first research question. For this, an analytical model is developed that computes the depth-varying wave energy (Section 3.2.2). Next, design options for the permeable structures are implemented in the analytical model to answer the second research question (Section 3.2.3). After this, the critical wave energy for *Avicennia Alba* Bl. across different ages and hydrodynamic conditions is calculated (section 3.2.4). Next, it is addressed which of the design options meet the critical wave energy thresholds (section 3.2.5). To answer the fifth research question, an expert elicitation is performed (section 3.2.6). To make the methodology clearer, a visualization of it is shown in Figure 13.

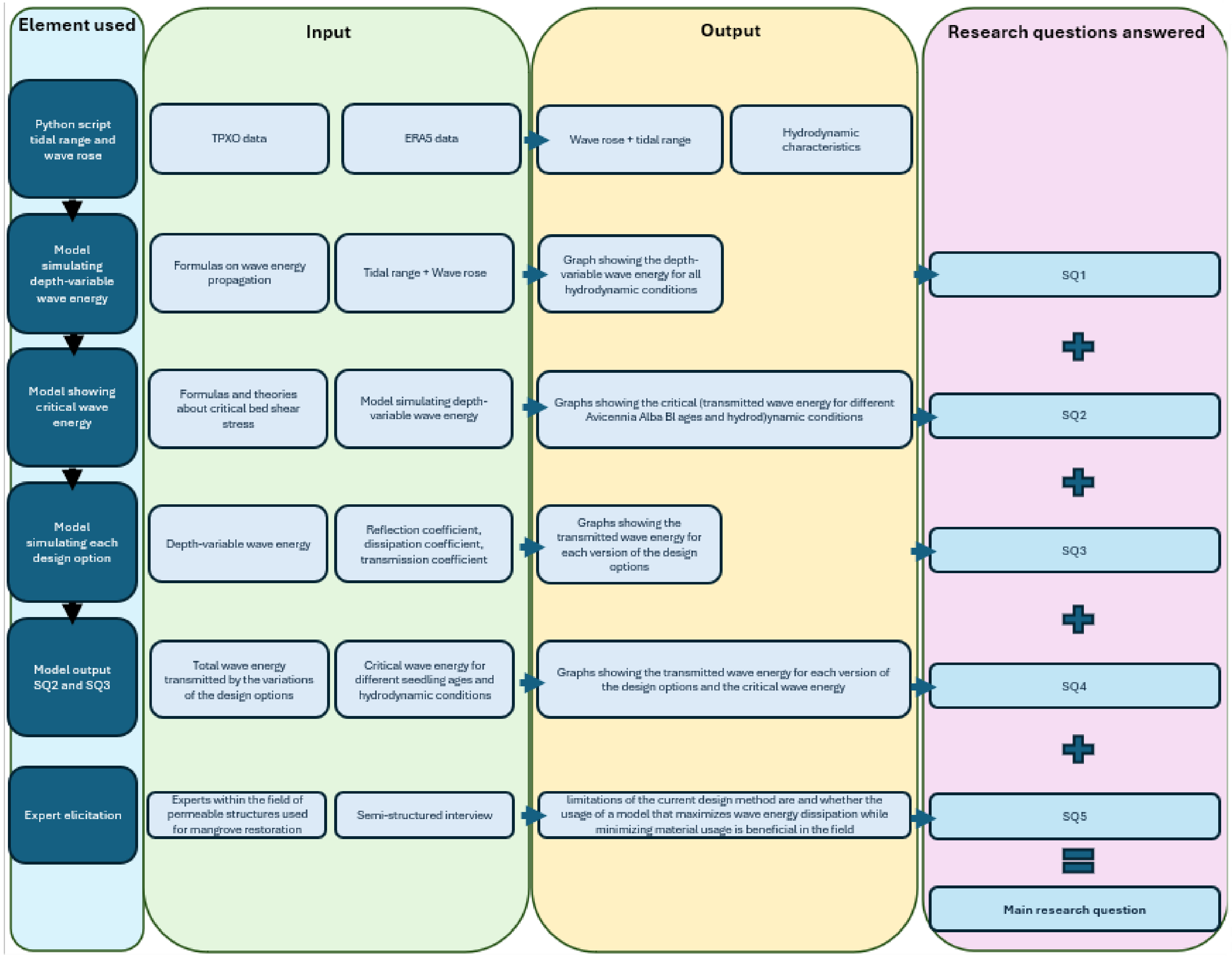

Figure 13: Visualisation of the research methodology

3.2.1. Description of model input data

Site conditions Demak Region

For the model input parameters, input data, and site conditions of the Demak region are explored. This includes, for example, data on hydrodynamic conditions such as water levels, water depths, significant wave heights, and wave periods. For this study, the water conditions that are described in Chapter 2 are considered.

Applicable water conditions

J. Winterwerp et al. (2020), mentions that permeable structures used for mangrove restoration are placed in shallow water conditions. This same paper mentions that the waves then behave as shallow water waves. Hence, the assumption of shallow water conditions is validated for this research.

One might wonder how big the inaccuracy is when shallow water conditions are applied in the case of intermediate water conditions. Two calculations are conducted. The first simulation shows the horizontal orbital velocity amplitude for different h/L-fractions between $1/24$ and ½. Here, h [m] represents the water depth and L [m] is the wave length. This analysis clarifies the differences in the horizontal orbital velocity between shallow, intermediate, and deep water conditions. Also, by looking at multiple h/L-fractions within either shallow water depth conditions, the transformation to either intermediate water depth conditions will become clearer. Equation 8 shows the computation of the wave length. Equations 8 to 14 show how the horizontal orbital velocity for intermediate and shallow water conditions are calculated. Equation 8 is used for calculating the wave length

$$L = \frac{g * T^2}{2 * \pi} * \tanh{(kh)} \tag{8}$$

where T [s] represents the wave period (Van Der Werf, 2024). For the first simulation, the general equation for calculating the wave length (Equation 8) is rewritten into a formula that calculates the wave period. This resulted in equation 9

$$T = \sqrt{\frac{2 * \pi * L}{g * \tanh{(kh)}}} \tag{9}$$

where, k represents the wave number (Van Der Werf, 2024). According to Dean & Dalrymple (1991), Equation 10 represents the calculation of the velocity under the wave for intermediate water depths

$$u_i = \frac{H_s}{2} * \sigma * \frac{\cosh k(h+z)}{\sinh kh} * \cos{(k_i x - \sigma t)} \tag{10}$$

where, H_s [m] represents the significant wave height, k_i represents the wave number for intermediate water depths, and σ [s^{-1}] represents the angular wave frequency. Equation 11 is used to calculate the wave length under intermediate water conditions

$$L_i = \frac{g * T^2}{2 * \pi} * \tanh(k_i * h) \tag{11}$$

where, k_i represents the wave number for the intermediate water conditions (Dean & Dalrymple, 1991).

Equation 14 is used for calculating the wave length in shallow water conditions (L_s)

$$L_s = T * \sqrt{g * h} \tag{12}$$

(Van Der Werf, 2024). The velocity under the wave for shallow water conditions (u_s) is calculated using Equation 13

$$u_s = \frac{g * H_s * k_s}{2 * \sigma} * \cos\,(k_s x - \sigma t) \tag{13}$$

(Dean & Dalrymple, 1991; Van Der Werf, 2024). The wave number for shallow water conditions will be calculated using Equation 14

$$k_s = \frac{2 * \pi}{L_s} \tag{14}$$

(Dean & Dalrymple, 1991; Van Der Werf, 2024)

Making a choice

First, the horizontal orbital velocity for shallow- and intermediate water wave conditions are compared (Appendix D). The outcome of the orbital horizontal velocity amplitude is shown in Appendix D.

3.2.2. Description of the analytical wave model

The model calculates the wave energy using the equations for the calculation of the potential (Equation 15) and kinetic energy (Equation 19) distribution. It should be noted that intermediate water conditions apply (see paragraphs 2.1.2 and 3.1.2).

The potential energy-density distribution is calculated using Equation 15

$$E_P(Z) = \overline{\int_{Z+\eta}^{\zeta} \rho * g * z * dz} - \int_{Z}^{0} \rho * g * z * dz = \frac{1}{16} * \rho * g * H_s^2 \; * \; 1 - \frac{sinh^2\big(k(Z+h)\big)}{sinh^2 kh} \tag{15}$$

where, $E_P(Z)$ [J/m²] represents the potential energy density in the water column between $z = Z + \eta(x,t)$ and $z = \zeta(x,t)$ (Dean & Dalrymple, 1991). Here, $z = Z + \eta(x,t)$ represents the vertical displacement oscillations of the water particles at a mean depth

$(z = Z)$ this is $z = Z + \eta(x, Z, t)$. The free surface is $\zeta(x, t) = \eta(x, 0, t)$. Where according to linear wave theory

$$\zeta(x,t) = \frac{1}{2} * H_s * cos(kx - \sigma t) \tag{16}$$

$$\eta(x,t) = \frac{sinh(k(Z+h))}{sinh\, kh} * \zeta(x,t) \tag{17}$$

And

$$\sigma^2 = g * k * tanh\, kh \tag{18}$$

The kinetic energy-density distribution is calculated using Equation 19

$$E_K(Z) = \overline{\int_{Z+\eta}^{\zeta} \frac{1}{2} * \rho * (u^2 + w^2) * dz} = \frac{1}{16} * \rho * g * H_s^2 \{1 - \frac{sinh^2(k(Z+h))}{sinh^2 kh}\} \tag{19}$$

where, $u(x, z, t)$ and $w(x, z, t)$ are orbital velocities are in horizontal and vertical directions, respectively (Dean & Dalrymple, 1991). The overlines in Equations 15 and 19 denote that the values are wave-averaged. So either over one wavelength (in x-direction), a wave period (in time t), or a wave phase ($\theta = kx - \sigma t$).

The orbital horizontal velocity (u) is greatest at the water surface. So it is known that at the water surface ($z = 0$) most of the energy is expected to be found. At $z = 0$ the orbital horizontal velocity (u) is the largest. At the sea bed $z = -h$, the least energy is expected, since the orbital horizontal velocity (u) is the smallest there. So

$$E_K(-h) = 0, \qquad E_K(0) = \frac{1}{16} * \rho * g * {H_s}^2 \tag{20}$$

$$E_P(-h) = 0, \qquad E_P(0) = \frac{1}{16} * \rho * g * {H_s}^2 \tag{21}$$

For the integration over the water column from the seabed to the water level, the following equations are

$$E_P(Z) = \frac{1}{16} * \rho * g * H_s^2 * \{\frac{sinh^2\big(k(Z+h)\big)}{sinh^2 kh}\} \tag{22}$$

$$E_K(Z) = \frac{1}{16} * \rho * g * H_s^2 * \{\frac{sinh^2(k(Z+h))}{sinh^2 kh}\} \tag{23}$$

The total incoming wave energy is calculated by summing the potential and kinetic energy of the incoming wave.

$$E_i(Z) = E_P + E_K \tag{24}$$

Equations 15 to 24 are used for the simulation of the total energy distribution over the water column. This distribution contains increments of 0.10 meters. However, this does not yet give the wave energy at different depths.

The model output shows the total energy of a certain wave height and the energy differences between two depths at varying depth levels. To determine the energy at specific depths in the water column, we used a function in Python that calculates the difference in energy between two depth intervals. Then, using another function, the average of each pair of consecutive depths was calculated, giving the mean value for each interval between depths. This then gives the amount of energy at the location of the midpoint of one 0.10-metre horizontal element.

3.2.3. Model schematization of permeable structures

The model output shows the total energy distribution. The model takes into account the water levels SLT, MLW, NLT, MSL, NHT, MHT, SHT, and storm conditions. For each water level, a worst-case scenario is selected from the wave heights (0.20, 0.50, and 1.20 meters) and wave periods (3, 4, and 5 seconds). This contains the largest wave height and longest wave period for that water level that is possible without the wave breaking. Wave breaking occurs once the wave steepness is greater than the maximum wave steepness (Equation 7).

Four design options are implemented. The design options are simulated by a number of parameters. The first one is bv [m] representing the thickness or diameter of horizontal elements. In this study bv has a value of 0.10 meters. In this research, horizontal plates are represented by a transmission, reflection, and a dissipation coefficient. K_t, K_r, K_d [-], respectively. For the horizontal elements, the transmission coefficient will have a value of 1. This is based on Gijón Mancheño et al. (2021a), where it was concluded that for structures where elements are placed directly against each other with no space between them, the energy is fully reflected, resulting in a reflection coefficient of 1. The transmission coefficient equals 0. The dissipation coefficient is not taken into account and equals 0. At depths where there are no horizontal elements, the transmission coefficient will equal 1 and the reflection coefficient will equal 0.

A description of these design options is shown below. The presentation of the energy reflection, energy dissipation, energy transmission, and wave height associated with this energy transmission per step taken is beneficial for the analysis that is computed to formulate an answer to sub-question 3.

Design option 0 represents the case where no permeable structure is implemented into the analytical model (Figure 14). The model output of this design option, is the same as that of the analytical wave model. The energy is expected to be fully transmitted.

In **design option 1**, a permeable structure consisting of horizontal bamboo plates attached to vertical bamboo poles from the seabed to 0.10 meters above the water level is simulated (Figure 14). To simulate the effect of the structure on the wave propagation, some simplifications and assumptions are made. First of all, since the horizontal bamboo plates are placed tightly together, the reflection coefficient is assumed to have a value of 1 (Gijón Mancheño et al., 2021a). In theory, the corresponding energy at depths where horizontal plates are placed will be fully reflected. This means that the dissipated and transmitted wave energy corresponds to 0.

In **design option 2,** an opening is created between the lower bamboo plate and the seabed. This opening is increased in steps of 0.10 meters. For each step, the energy reflection, energy dissipation, energy transmission, and wave height associated with this energy transmission are represented. The maximum gap height is from the seabed to the sea level. This is represented as design option 2 in Figure 14. The simplification is made that the horizontal elements will represent a reflection coefficient of 1. There are no horizontal elements present; the reflection coefficient will be 0, and the transmission coefficient will be equal to 1. The dissipation coefficient is in all cases 0.

For **design option 3,** the same is done, but here the structure is filled with bamboo plates from the sea bed level to the sea water level in steps of 0.10 meters. The gap between the horizontal elements and the sea water level will thus decrease. Again, for each step, the energy reflection, energy dissipation, energy transmission, and wave height associated with this energy transmission are represented (Figure 14).

In **design option 4**, a practical solution which is based on expert judgment. The structure is only filled with bamboo plates between MHT and MLT (Figure 14). Again, for each step, the energy reflection, energy dissipation, energy transmission and wave height associated with this energy transmission is represented. The hypothesis is that this design option is the most efficient one.

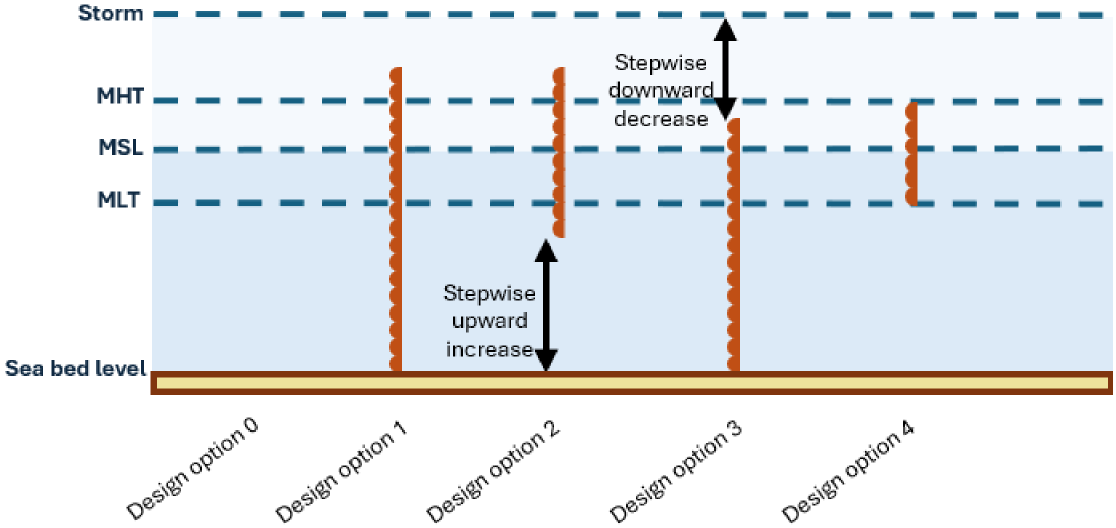

Figure 14: Sketch of the different design options for the permeable structures that will be implemented into the analytical Python model

3.2.4. Model validation

For this design, wave flume experiment data does not yet appear to be publicly available. This presents problems in calibrating and validating a prepared model that optimizes the design of such permeable vertical structures under varying hydrodynamic conditions. However, a wave flume experiment is conducted by two Bachelor students of the 'Hogeschool van Arnhem en Nijmegen' (Chan & Mekkelholt, 2025). During these experiments, the students measured the wave heights in front of and behind scaled permeable structures of designs 1-4. This experiment was conducted in the wave flume. As wave flume input, they used wave steepnesses of 1, 2, and 4 %. Furthermore, they used water depths of 0.20, 0.24, and 0.30 m with wave lengths of 2.10, 2.30, and 2.50 m, respectively. Wave heights of 0.03, 0.05, 0.08, and 0.09 meters, respectively, were used. During the experiment, only one wave gauge was available. This means that the incoming and transmitted waves couldn't be measured in the same run. This might have resulted in inaccuracies in the measurement data. Furthermore, the wave period and wave energy were not measured or calculated.

A few inaccuracies in the measurement campaign and data were observed. The measurement results lack the first case, where the structure fills the entire water column. Similarly, for the structure placed in a water depth of 0.30 meters and a wave height of 0.09 meters, the step where no horizontal elements are present is lacking. From the measurement results, for a wave height of 0.08 at a water depth of 0.24 meters and a construction height of 0 meters, a transmission coefficient of 1.1 was observed. This would mean that energy was generated in the experiment. In addition, the transmission coefficient is also 1.1 at a water depth of 0.30 meters with a wave height of 0.09 meters and a construction height of 0.06 meters. Due to these inaccuracies, the wave flume experiment is assumed to be insufficient for model calibration. Therefore, the results will be used for a comparison instead of a calibration.

After the design options one through four are implemented, the model results will be compared to outcomes of the wave flume experiment. This will be done for design option 2. By doing so, the structures' height divided by the water depth and their related transmission factor will be plotted. Since the wave period was not given, this is calculated. Also, the incoming and transmitted energy is calculated using the measured significant wave height and transmitted wave height. Based on the given 'gap', the structures' length used in the experiments is calculated. The construction height is divided by the water depth and plotted against its transmission coefficient.

In the created model, the worst-case scenarios of the wave flume experiment are used as input data for the analytical wave model. These are water depths of 0.20, 0.24, and 0.30 meters with wave heights of 0.08, 0.08, and 0.09 meters and wave periods of 1.16, 1.21, and 1.27 seconds. The output of the analytical wave model under these conditions is used as model input for the model of design option 2. The used construction height is also divided by the water depth and plotted against its transmission coefficient. This result is plotted in the same graph as the wave flume experiment results. This gives a comparison between the model output and the wave flume results. An example of such graphs is shown below.

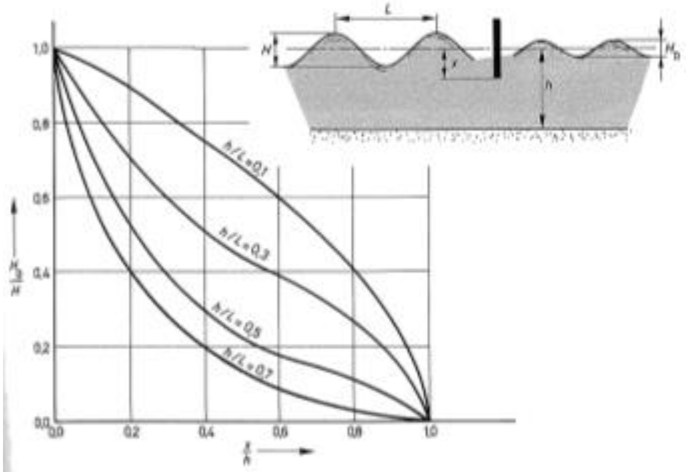

Figure 15: Graph Nortier & de Koning (1996) showing the transmission factor corresponding to different construction height water depth ratios for different wave steepnesses

3.2.5. The critical wave energy for mangrove establishment

Maximum resistible bed shear stresses and erosion

Accordingly to Balke et al. (2015), for a mangrove propagule, there is a maximum critical erosion depth that a propagule is able to resist. This is calculated using Equation 25

$$RS_{max} = 1.921 * ln(a) - 3.2337 \quad (25)$$

where, RS_{max} [cm] is the maximum critical erosion depth and a represents the age of the mangrove seedlings in days. The seedling root length after establishment is calculated using Equation 26

$$R_i = R_{i,0} + (M_i \ * G_R \ * A_i)^{c_2} \quad (26)$$

where, R_i represents the root length of the seedlings, G_R represents the growing speed in cm per day, A_i represents the age of the seedlings in days, and M_i represents the growth limitation/acceleration factor (Gijsman et al., 2024). These are species-specific values and could thus vary per mangrove restoration project. Except, of course, if the same mangrove species are present at the mangrove restoration project.

According to Gijsman et al. (2024), the mangrove seedlings are dislodged when the bed shear stress is greater than the bed shear stress tolerance. The maximum allowed bed shear stress at seedling establishment $\tau_{cr,i}$ [N/m^2] is calculated using Equation 27

$$\tau_{cr,i} = \tau_{cr,i0} + G_{\tau,i} \ * \ R_i \quad (27)$$

where, $G_{\tau,i}$ [N/ m^3] represents a growth coefficient determining the (linear) increase of the critical bed shear stress concerning the seedling root length. Bed shear stresses are caused by flows and waves. The bed shear stress caused by flow velocity is calculated by the use of Equation 28

$$\tau_f = \frac{n}{\sqrt[6]{h}} * \rho * g * \bar{u} * |\bar{u}| \quad (28)$$

where, n [-] represents the Manning roughness coefficient, h [m] represents the water depth and $\bar{u}$ represents the depth-averaged flow velocity (Balke et al., 2011). The bed shear stress caused by waves could be calculated using Equation 29

$$\tau_w = \frac{1}{2} * \rho * f_w * u_{orb}{}^2 \quad (29)$$

The bed shear stress caused by both flow and waves should not exceed $\tau_{cr,i}$. This total bed shear is calculated using Equation 30

$$|\tau_{fw}| = a_r * |\tau_f| + |\tau_w| \tag{30}$$

where, a_r [-] represents a reduction factor for the bed shear stress caused by the flow/current caused by the waves (Balke et al., 2011). This reduction factor is calculated using Equation 31

$$a_r = [ln(\frac{30 * \delta}{k_a})/ln(\frac{30 * \delta}{k_s})]^2 * [\left\{-1 + ln(\frac{30 * h}{k_s})\right\} / \left\{-1 + ln(\frac{30 * h}{k_a)})\right\}]^2 \tag{31}$$

where, k_s [m] represents the roughness height of the bed material, k_a [m] represents the apparent roughness height of the bed material (Balke et al., 2011). This is calculated using Equation 32

$$k_a = k_s * \exp \frac{\gamma * \widehat{U_\delta}}{\bar{u}} \quad \text{for} \quad \frac{\widehat{U_\delta}}{\bar{u}} \leq 5 \tag{32}$$

where, γ is a coefficient representing the angle between the wave and the current. When waves are assumed to have the same direction as the current, γ should equal 0.75 (Balke et al., 2011). $\widehat{U_\delta}$ represents the maximum horizontal orbital velocity at the bed. δ represents the bed boundary thickness, which is calculated using Equation 33

$$\delta = 0.2 * \widehat{A_\delta} * (\frac{\widehat{A_\delta}}{k_s})^{-0.25} \tag{33}$$

where, $\widehat{A_\delta}$ represents the maximum horizontal excursion of the water particles at the bottom (Balke et al., 2011). This is calculated by the use of Equation 34

$$\widehat{A_\delta} = \frac{H}{2 * sin\,h\,kh} = \frac{\widehat{U_\delta}}{\sigma} \tag{34}$$

Next to the exceedance of the maximum allowed bed shear stress at seedling establishment, dislodgement of seedlings takes place when the erosion exceeds the critical erosion depth $E_{cr,i}$ [m] (Gijsman et al., 2024). This critical erosion depth is calculated using Equation 35

$$Er_{cr,i} = E_{cr,i0} + G_{E,i} * ln(H_i) \tag{35}$$

where, H_i [m] represents the seedling shoot length, $E_{cr,i0}$ [m] represents the initial erosion depth tolerance, and $G_{E,i}$ [-] represents a growth coefficient for the erosion depth tolerance (Gijsman et al., 2024).

It should be noted that only the shear stress caused by waves will be taken into account when calculating the critical bed shear stress in the model. It is assumed that all bed shear stress is caused by waves.

From maximum bed shear stresses to a maximum (transmitted) wave energy

The maximum allowable friction force is converted into a maximum allowable wave energy. The critical bed shear stress is substituted in eq.(28) for the total bed shear stress to resolve the critical wave height and energy:

$$\tau_w = \tau_{cr,i} - a_r * |\tau_f| \quad (36)$$

$$\frac{1}{2} * \rho * f_w * u_{orb}^2 = \tau_{cr,i} - a_r * |\tau_f| \quad (37)$$

$$\frac{1}{2} * \rho * f_w * \left(\frac{\sigma * \frac{1}{2} * H_{critical}}{sinh(k * h)}\right)^2 = \tau_{cr,i} - a_r * |\tau_f| \quad (38)$$

$$H_{critical} = \frac{2 * sinh(k * h)}{\sigma} * \sqrt{\frac{2 * (\tau_{cr,i} - a_r * |\tau_f|)}{\rho * f_w}} \quad (39)$$

$$E_{critical} = \frac{2 * sinh(k * h)}{\sigma} * \sqrt{\frac{2 * (\tau_{cr,i} - a_r * |\tau_f|)}{\rho * f_w}} \quad (40)$$

For the parameter values in the calculations, the values mentioned in Balke et al. (2011) and Gijsman et al. (2024) are used. These parameters are based on *Avicennia Alba* Bl. of an age of 365 days. However, calculations for several ages are made using these parameters. Starting with an age of of 190 days. This age will be increased by 30 days. The ages calculated are thus 190, 220, 250, 280, 310, 340, 365 and 545 days. This way, the critical wave energy corresponding to the hydrodynamic conditions and different seedling ages from 6 months to 1.5 years are explored.

3.2.6. The optimum design

To enable mangrove restoration, sufficient wave dampening is required with a transmitted wave energy below the critical wave height.

The model is used to determine which placements of the horizontal elements of the structure correspond to this transmitted wave height for both design options 2 and 3. Based on this, the necessary construction height of the dam of the optimized design options 2 and 3 is determined by comparing the critical energy with the cumulative total wave energy obtained by different variants of the design options.

The design that meets the objective, a bed shear stress lower than the critical bed shear stress, while using the least material, is considered to be the optimal design.

3.2.7. Limitations & benefits of the design method

To find out what the limitations of the current design method are and whether the usage of a model that maximizes wave energy dissipation while minimizing material usage is beneficial according to experts within the field, or not, an expert elicitation is carried out. To perform an expert elicitation 7 steps are conducted (Knol et al., 2010). These steps are shown in Figure 16.

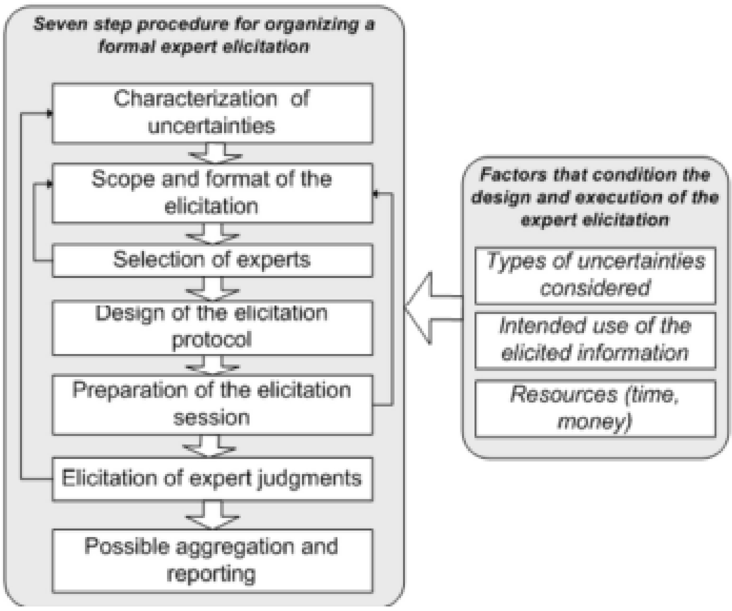

Figure 16: 7 Steps of an Expert Elicitation (Knol et al., 2010)

Purpose

The expert elicitation has several purposes. The first purpose is to find out what the limitations of the current design method are in practice. The second purpose is to find out whether the usage of a model that maximizes wave energy dissipation while minimizing material usage is beneficial according to experts within the field, or not. The third purpose is to find out what characteristics the model should have to be useful in the field. The fourth purpose is to determine how likely the model will be used by experts in the field.

Scope and format

For the expert elicitation, a group of 6 experts is asked to participate. These are experts within the field of 'permeable structures for mangrove restoration'. The group of participants consists of researchers, engineers, and on-site experts. After this is done, the scope and format of the expert elicitation are described. This group of 6 experts consists of three experts from Witteveen+Bos, one of EcoShape, who have on-site experience with the use of permeable structures for mangrove restoration in Indonesia. Furthermore, one or two experts who have done research on permeable structures for mangrove restoration projects will be questioned. The last group of experts consists of one or two 2 experts from the University of Twente, who have experience with permeable structures used for mangrove restoration projects. The participants are shown in the table below

Table 3: Overview of the participants of the Expert Elicitation

Name	Role	Organisation	Expertise
ir. T. Wilms	Engineer & on-site expert	Witteveen+Bos	Engineer + on-site experience in mangrove restoration projects
ir. G. Klopman	Engineer & on-site expert	Witteveen+Bos	Hydro morpholic modelling , Physics and on-site experience
dr. ir. E. Horstman	Researcher / University associate professor	University of Twente	Research on mangrove restoration
A. Reniers	Researcher	Delft University	Research on the influence of structures on wave propagation
ir. J. Noordermeer	Engineer and on-site expert	Witteveen+Bos	Engineer and on site-experience in mangrove restoration projects

A. Astra	on- site expert	Wetlands international / Ecoshape	On site experience in mangrove restoration projects

Open-ended questions

During the fourth step of the expert elicitation, the questions are developed. Since it will gather qualitative data, open-ended questions about assumptions and definitions are included. Also, vague wordings are avoided as much as possible. The list with questions is shown in the table below.

Table 4: Overview questions asked during expert elicitation

Question nr.	Description
1	What is your expertise within permeable structures used for mangrove restoration projects, particularly in relation to regulating wave energy and wave height?
2	Where did you get this expertise?
3	How would you describe the current way of designing permeable structures and the varying designs used in mangrove restoration projects, especially in terms of wave energy dissipation and wave height reduction?
4	What are the limitations of the current design method of permeable structures used in mangrove restoration projects in effectively regulating wave energy and wave height?
5	When designing a permeable structure for mangrove restoration, where do you get the design wave height, water depth and wave periods and how big are those approximately? (Only for T. Wilms, A.Astra, J.Noordermeer)
6	When designing a permeable structure, what conditions do you take into account?
7	Do you take daily or storm conditions into account for the design of permeable structures?

Follow-up question if storm conditions apply: Do you take a storm with a return period of 1 , 5 or 10 years into account?

8	What age of mangroves will the permeable structure be based in relation to their persistence to wave energy?
9	What (transmitted) wave height and wave energy levels make mangrove restoration in the first stage (1 till 5 years) possible?
10	In your opinion, what are the most critical factors for a permeable structure to be effective in regulating wave energy and wave height for mangrove restoration?
11	The model created contains some assumptions and simplifications related to wave energy and wave height regulation. What are the opportunities and risks you see per assumption/simplification?
12	Do you believe that a model that shows the energy distribution over the water column so it is known where energy should be reflected or dissipated to meet a wave energy/height threshold for mangrove seedlings to survive, is beneficial for the design of permeable structures? Why or why not?
13	What characteristics should the model have to be practically useful in the field, specifically for designing structures that reduce wave energy and wave height?
14	What makes it more attractive to use the model for designing permeable structures that regulate wave energy and wave height?
15	What makes it less attractive to use the model for designing permeable structures that regulate wave energy and wave height?
16	How likely are you to use such a model in your design or research, particularly for projects focused on mangrove restoration and protection against erosion?

Briefing document

During the fifth step, a briefing document that contains relevant background information on the topic and the master thesis is shared with the participants. This is done before the interview takes place. The briefing document is attached in Appendix A.

Computing the expert elicitation

The sixth step is the expert elicitation. The expert elicitation starts with a small introduction to give an overview of the study and it is explained to the experts why their role is important. After the introduction, the semi-structured interview takes place. The entire semi-structured interview phase is recorded.

Reporting

The seventh step is reporting. During this step, the process, expert selection, interview methods, and possible biases are documented. The reporting helps answer SQ6.

4. Results

This chapter describes the research findings. First, the wave energy distribution over depth is discussed (section 4.1). Then, the simulations of the impact of the design options on the wave energy distributions from section 4.1 will be discussed. This is done in sections 4.2 to 4.3. It should be noted that the calculations are based on the worst-case scenario conditions. For each water depth, the corresponding highest significant wave height and wave period possible without wave breaking are used as input data. The results are presented for the water levels MLT, MSL, MHT and the storm condition.

4.1. Base model (Design option 0)

The analytical wave model simulates the cumulative total vertical energy distribution of an incoming wave (Figure 17). Figure 17 shows that most of the cumulative total wave energy is located near the water level (z=0). This corresponds to the theory presented in Chapter 2. When assessing wave energy, the significant wave height is the primary factor influencing the wave energy. For any given significant wave height, the energy remains constant across different water levels. In other words, waves of the same height will carry the same maximum energy, even if the water level is higher or lower.

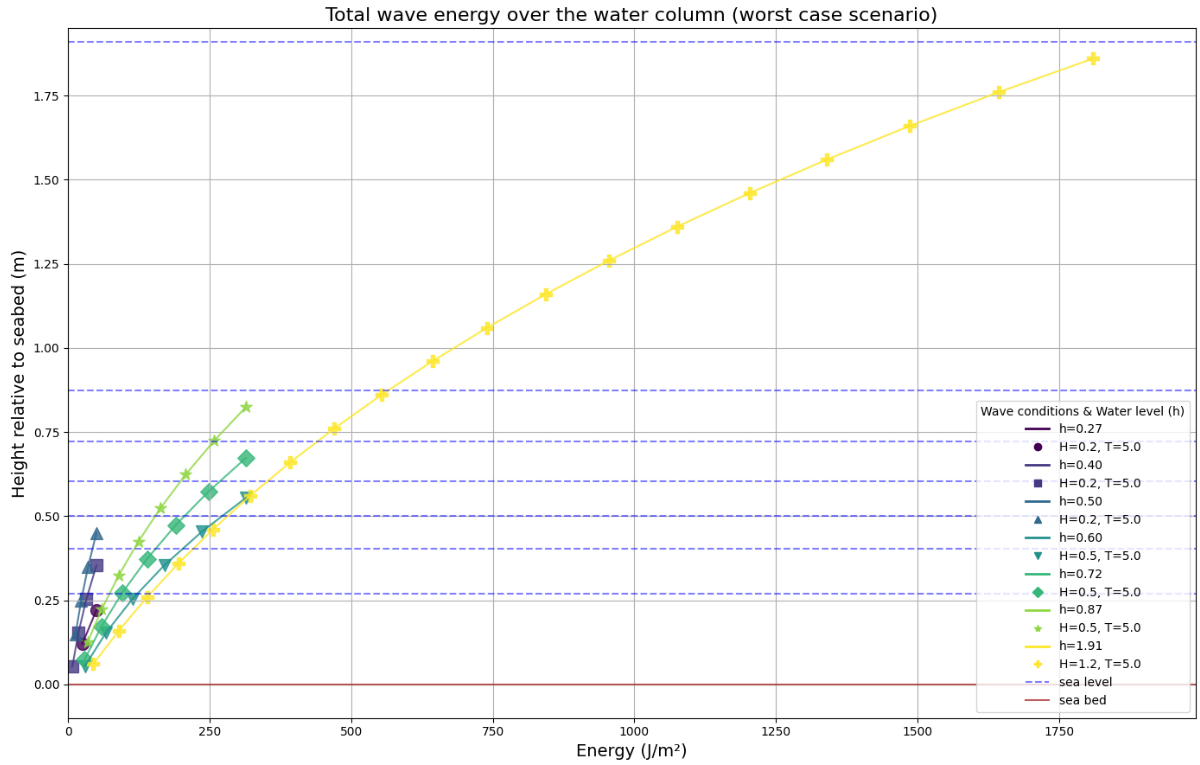

Figure 17: The graph shows the cumulative total wave energy distribution over the water column, with the wave energy in J/m² on the x-axis. On the y-axis, the height relative to the seabed is shown. Each marker point represents the total wave energy at that height relative to the seabed.

Next to the total energy distribution, the model also computes the depth-specific energies at intervals of 0.10 m, starting 0.05 m below sea water level or above the seabed. This gives insight into how much energy is at each depth interval approaching the horizontal elements. The depth-specific energies are shown as bars in Figure 18. Again, the represented wave energy at each depth is based on the worst-case scenario conditions, corresponding to the highest possible wave height and wave period.

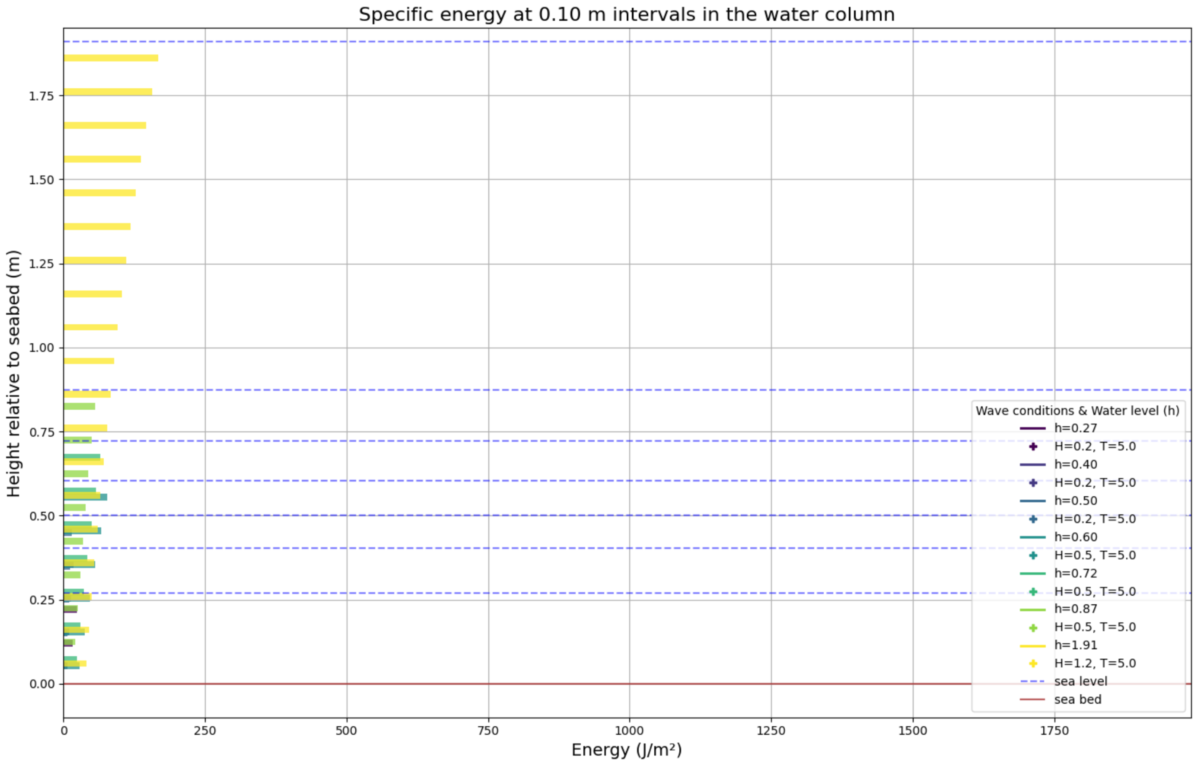

Figure 18: Wave energy corresponding to specific points in the water column. The x-axis shows the wave energy in J/m^2, and the y-axis shows the height relative to the seabed. Each bar represents the depth-specific wave energy at that height relative to the seabed.

A combination of both the depth-specific wave energies and the cumulative depth-specific wave energies is shown in Figure 19.

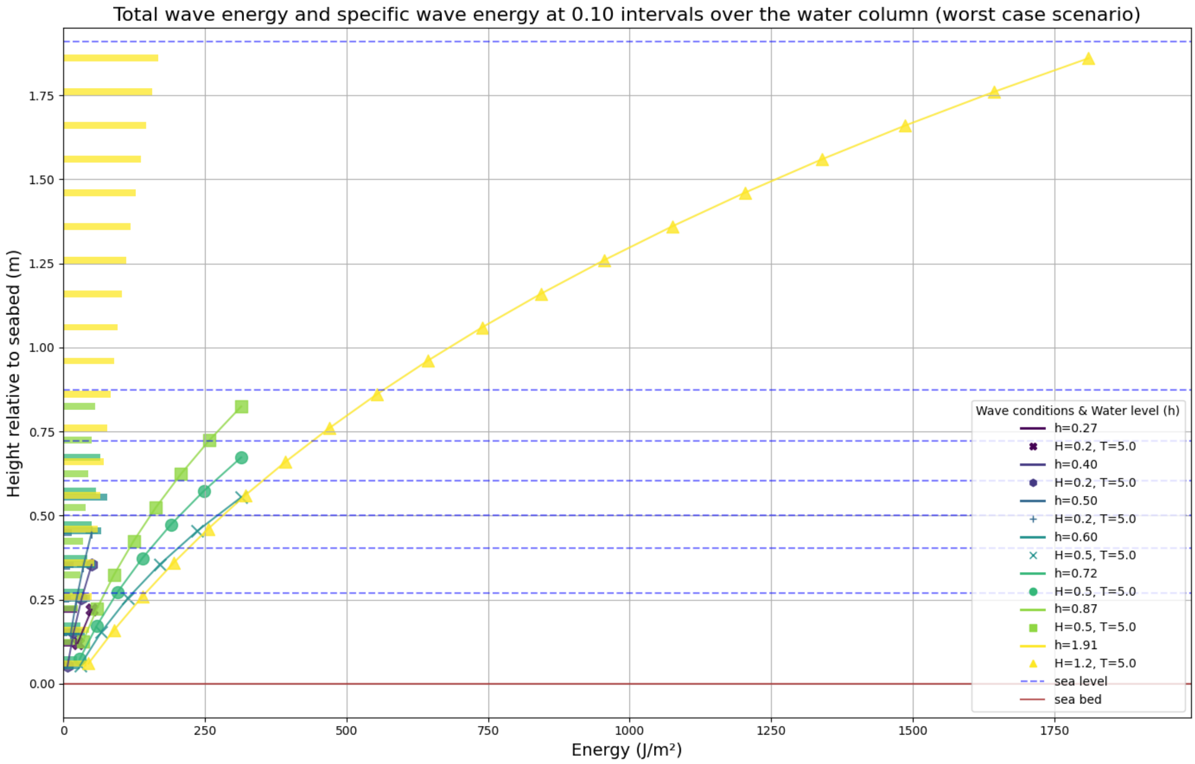

Figure 19: Combination of the representation of the wave energy corresponding to specific points in the water column and the cumulative total wave energy at 0.10-meter intervals in the water column. The x-axis shows the wave energy in J/m^2, and the y-axis shows the height relative to the seabed. Each bar represents the depth-specific wave energy at that height relative to the seabed. The lines represent the cumulative total wave energy distribution.

The result in Appendix E shows the total energy distribution of a wave with a wave height of 0.20, 0.50, and 1.20 meters. Wave periods of 3,4, and 5 seconds, respectively.

4.2. The effect of permeable structures on wave energy distribution

4.2.1. Design option 1

The results for design option 1 illustrate how energy from an incoming wave propagates through a structure that is placed from the water level to the seabed (Figure 20). In this figure, design option 1 is represented as a structure that fills the water column (represented as the vertical brown line). The simulation focused on the 'worst case scenarios,' which represent the highest possible wave height and period for each water level. For all these water levels, it is observed that the structure reflects all incoming energy (the green line in Figure 20). Since the depth-specific energy is increasing while getting closer to the sea level, the green line is increasing simultaneously. Consequently, the total transmitted energy for design option 1 is zero (represented as the red line in Figure 20). This was expected, as the energy at each depth is multiplied by a reflection coefficient of 1, resulting in total reflection. The incoming depth-specific wave energies are thus multiplied by one to calculate depth-specific reflected wave energy. It is observed that the green line is increasing with water level.

Appendix F presents a complete overview of the results for the simulation of design option 1 for water levels: SLT, NLT, NHT, AND SHT.

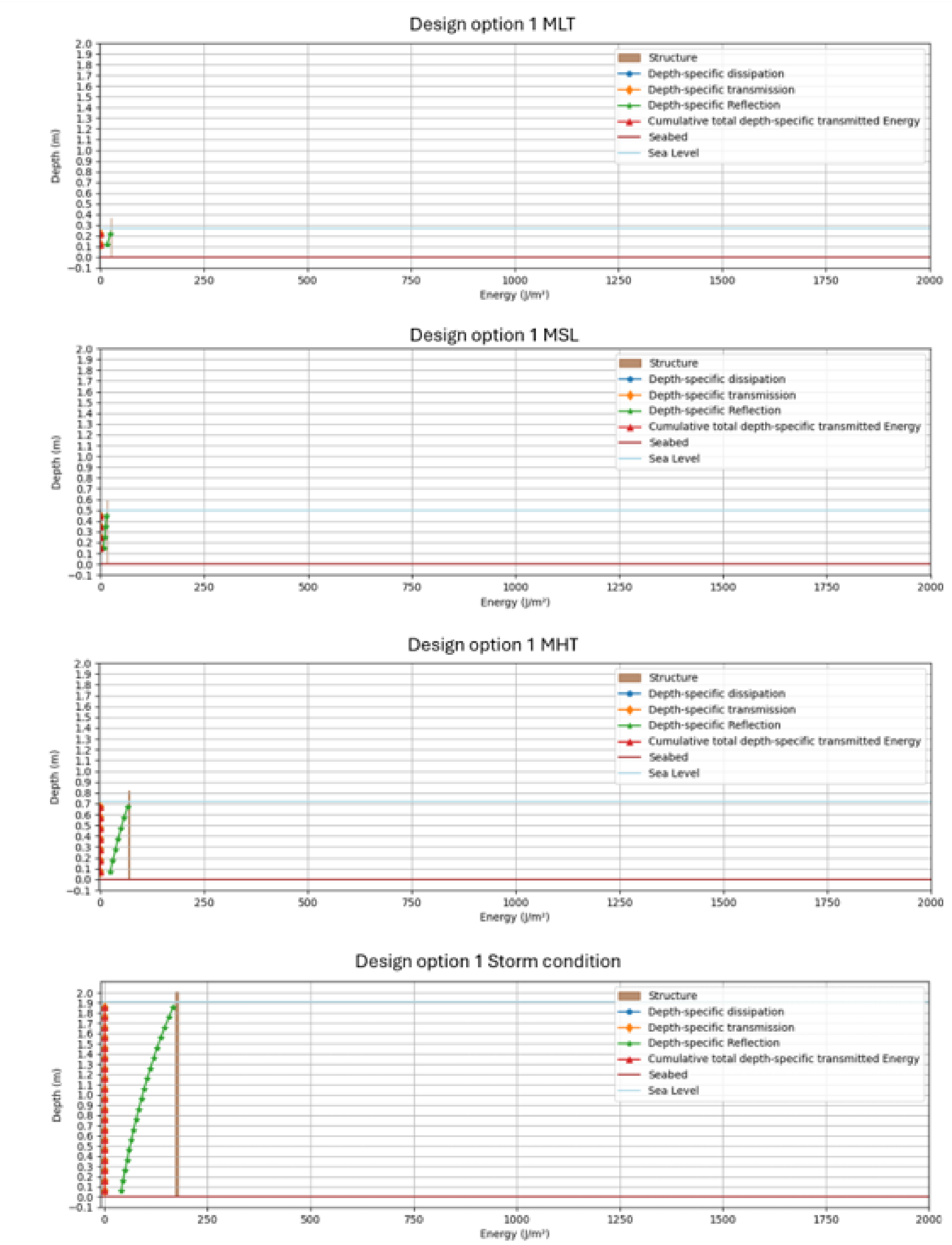

Figure 20: Visualisation of the simulation of design option 1 for MLT, MSL, MHT, and the storm condition. The x-axis shows the wave energy in J/m², and the y-axis shows the height relative to the seabed. The vertical brown line represents the simulated structure. The green line represents the depth-specific reflected wave energy. The orange

line represents the depth-specific transmitted wave energy. The red line represents the cumulative total transmitted wave energy at 0.10-meter intervals in the water column.

4.2.2. Design option 2

Figure 21 illustrates how energy from an incoming wave propagates through Design Option 2. Design option 2 shows the construction where, at the first step, the structure fills the entire water column. This part of the simulation of Design option 2 equals the simulation of Design option 1. An overview of the simulation of this first step for MLT, MSL, MHT, and a storm condition is shown in Figure 20. Starting from the bottom to the sea level, horizontal elements will disappear from the structure in 0.10 m intervals. Figure 21 contains fractions of the simulation for MHT. These represent the phase where the structure (represented as the vertical brown line) is filling the water column halfway (step 4) and the phase where no structure is left (step 8).

For all water levels, it is shown that the structure reflects all incoming energy at depths where horizontal elements are present (Figure 21). The incoming depth-specific wave energy at depths without such elements is fully transmitted (Figure 21). Per depth, the total cumulative transmitted wave energy is represented as the red line in Figure 21. Since this is therefore the cumulative sum of the depth-specific transmitted wave energies, it is substantially larger than the orange line. Since the depth-specific energy increases while getting closer to sea level, the reflected, transmitted, and cumulative sum of the transmitted wave energy is also higher when closer to sea level. Since only the depth-specific energies where the structure is present are completely reflected, the remaining energy will be transmitted. This causes the reflected energy (green line) and the transmuted energy (orange line) to merge.

The model outcome aligns with expectations, as the energy at depths with horizontal elements is multiplied by a reflection coefficient of 1, resulting in complete reflection, whereas at depths lacking horizontal elements, the energy is multiplied by a transmission coefficient of 1, with a reflection coefficient of 0. Obviously, the greater the significant wave heights, the greater the energy transmitted or reflected at different points in the water column.

Appendix F presents a complete overview of the results for the simulation of design option 1 for water levels: SLT, NLT, NHT, SHT, and a storm condition.

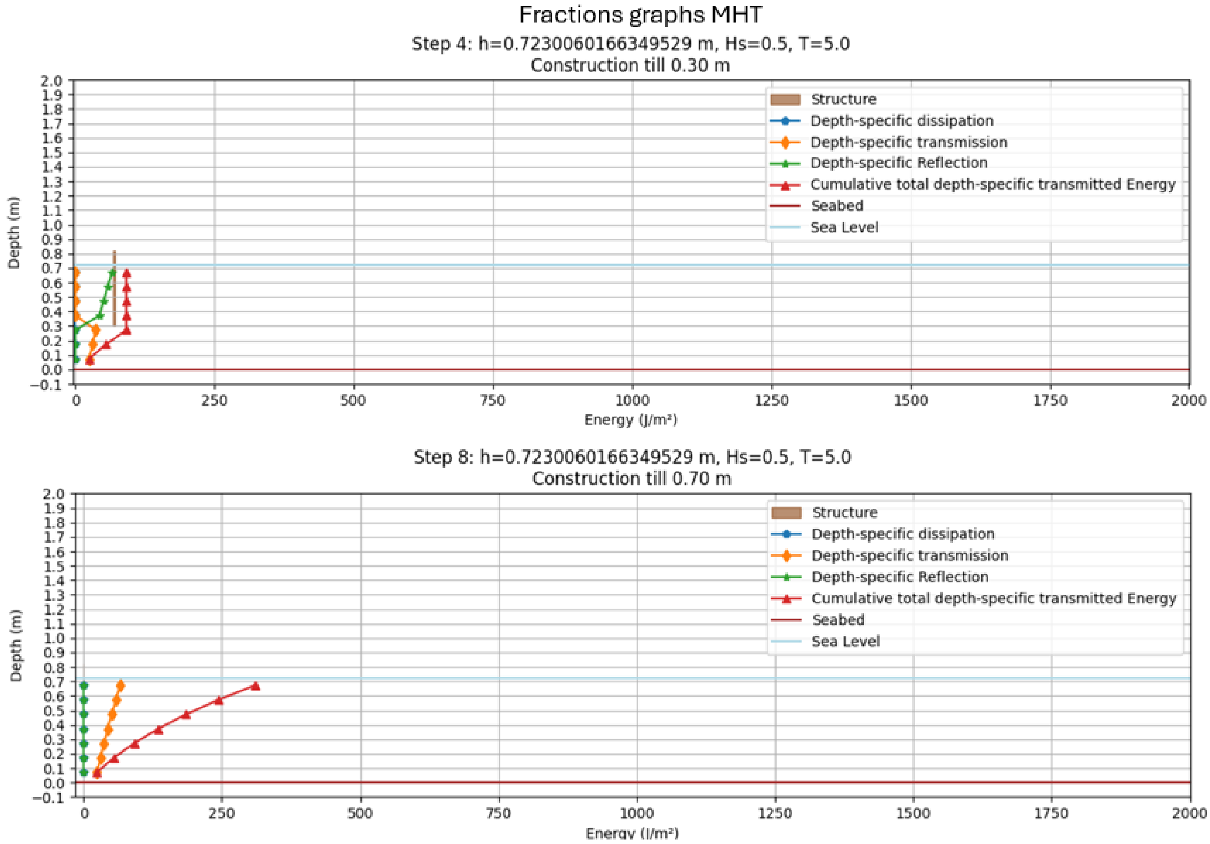

Figure 21: Visualization of the simulation of design option 2 for MLT, MSL, MHT, and the storm condition. The x-axis shows the wave energy in J/m^2, and the y-axis shows the height relative to the seabed. The vertical brown line represents the simulated structure. The green line represents the depth-specific reflected wave energy. The orange line represents the depth-specific transmitted wave energy. The red line represents the cumulative total transmitted wave energy at 0.10 intervals in the water column.

4.2.3. Implementation of design option 3

In contrast to Design option 2, in Design option 3, the structures' length increases from the seabed to the water level. The results of design option 3 are similar to those of design option 2. Again, the horizontal elements fully reflect the incoming wave energy.

Figure 22 shows the first step of the simulation of Design option 3 for MLT, MSL, MHT, and a storm condition. This first step of the simulation represents the situation in which no structure is present. Figure 23 shows fractions of the model output of the simulation of Design option 3 for MHT. These represent the phase where the structure (represented as the vertical brown line) is filling the water column halfway (step 4) and the phase where the structure fills the water column (step 8).

Again, only the depth-specific energies where the structure is present are completely reflected; the remaining energy is transmitted. This causes the reflected energy (green line) and the transmuted energy (orange line) to merge. Again, the closer the depth-specific reflected or transmitted energies are to the sea level, the bigger their values are. The red line represents the total energy transmuted at 0.10-metre intervals in the water column. This is the cumulative sum of the depth-specific transmuted energies.

Similar to Design option 2, the total cumulative transmittable wave energy at 0.10 meter intervals increases rapidly as more depth-specific energies are transmitted.

A complete overview of the results of the simulation of design option 3 is shown in Appendix F.

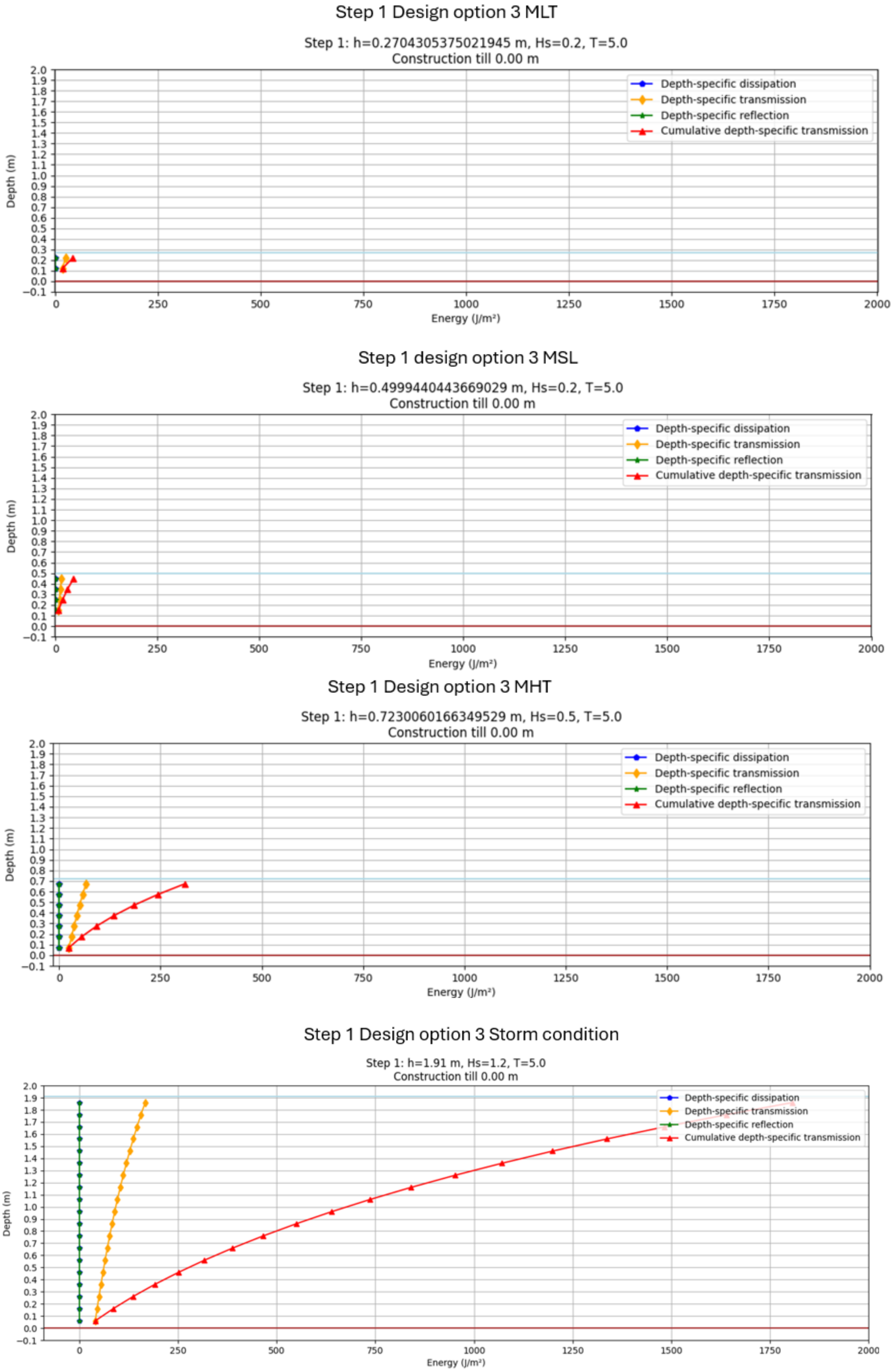

Figure 22: Visualization of the first step of the simulation of design option 3 for MLT, MSL, MHT, and the storm condition. The green line represents the depth-specific reflected wave energy. The orange line represents the depth

specific transmitted wave energy. The red line represents the cumulative total transmitted wave energy at 0.10 intervals in the water column.

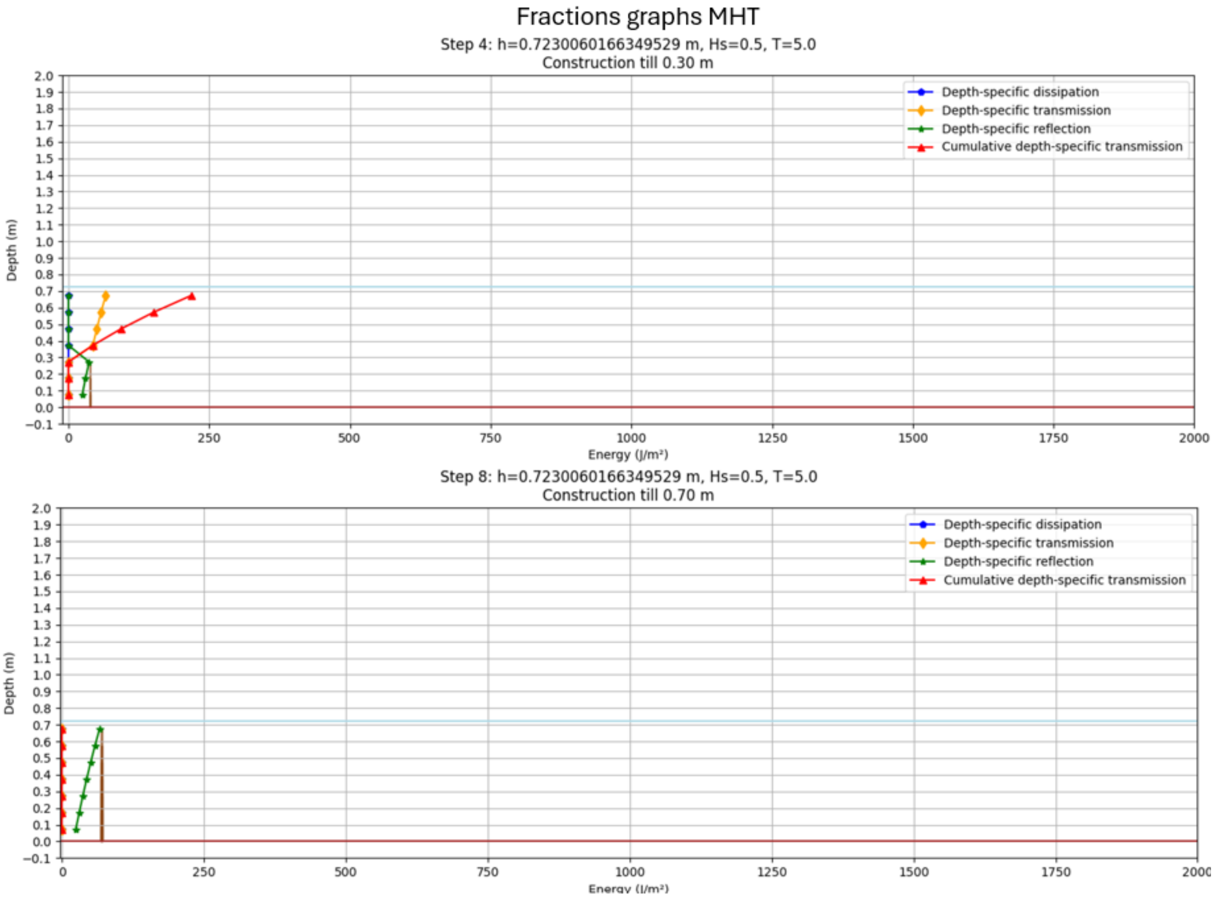

Figure 23: Visualization of the simulation of design option 3 for MLT, MSL, MHT, and the storm condition. The x-axis shows the wave energy in J/m^2, and the y-axis shows the height relative to the seabed. The vertical brown line represents the simulated structure. The green line represents the depth-specific reflected wave energy. The orange line represents the depth-specific transmitted wave energy. The red line represents the cumulative total transmitted wave energy at 0.10 intervals in the water column.

4.2.4. Implementation of design option 4

Figure 24 shows an overview of the simulations of design option 4 for the water levels MLT, MSL, and MHT. As for Design options 1, 2, and 3, the structure is shown as a vertical brown line.

Only the depth-specific energies where the structure is present are completely reflected; the remaining energy is transmitted. This causes the reflected energy (green line) and the transmuted energy (orange line) to merge. Again, the closer the depth-specific reflected or transmitted energies are to the sea level, the bigger their values are. Similar to Design options 2 and 3, the total cumulative transmittable wave energy at 0.10 meter intervals increases rapidly as more depth-specific energies are transmitted. It was expected that for MSL and MLT, the elements placed above the water level would not influence the total cumulative transmitted energy. However, these elements do affect the energy distribution at MHT. Since the water level here is a lot higher than for MLT or MSL, the energy distribution also extends a lot further. In case MHT occurs and no elements are placed above MSL, the energy occurring at depths above MSL will be fully transmitted. This can cause excessive bed shear stress behind the structure.

The design with the least amount of material that meets the critical bed shear stress is discussed in Section 4.6. A comprehensive overview of the simulations of all water levels is provided in Appendix F.

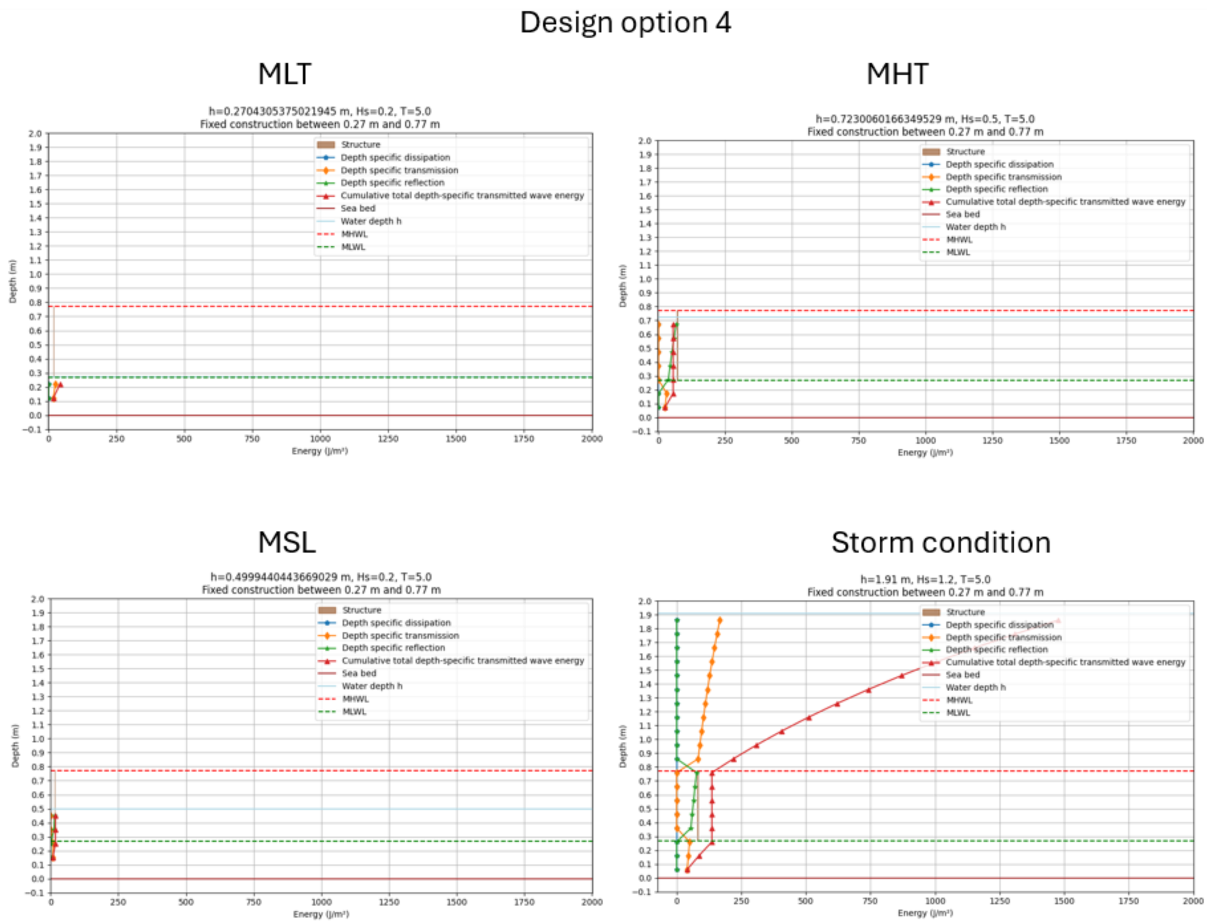

Figure 24: Visualization of the simulation of design option 4 for MLT, MSL, MHT, and the storm condition. The x-axis shows the wave energy in J/m^2, and the y-axis shows the height relative to the seabed. The vertical brown line represents the simulated structure. The green line represents the depth-specific reflected wave energy. The orange line represents the depth-specific transmitted wave energy. The red line represents the cumulative total transmitted wave energy at 0.10 intervals in the water column.

4.2.5. Comparison of the design options

Figure 25 shows the amount of total transmitted energy generated by different Construction Heights per Design Option. This analysis was performed for the "Storm Condition".

Design Options 1, 2, and 3 show that for the scenario where the structures fill the water column, the total cumulative energy transmuted is equal to 0. Design Option 4 consists of a 0.50-meter fixed structure. The total cumulative transmittable energy generated by this Design Option is achieved with a less structural length than Design Option 3. However, the structural length required for Design Option 4 to achieve this amount of transmuted energy is greater than the structural length that would be required for Design Option 2. In addition, Design Option 2 requires the least construction height to generate the same amount of total cumulative transmitted wave energy compared to Design Option 3. In terms of construction height, it seems that Design Option 2 would be the most "optimal" design.

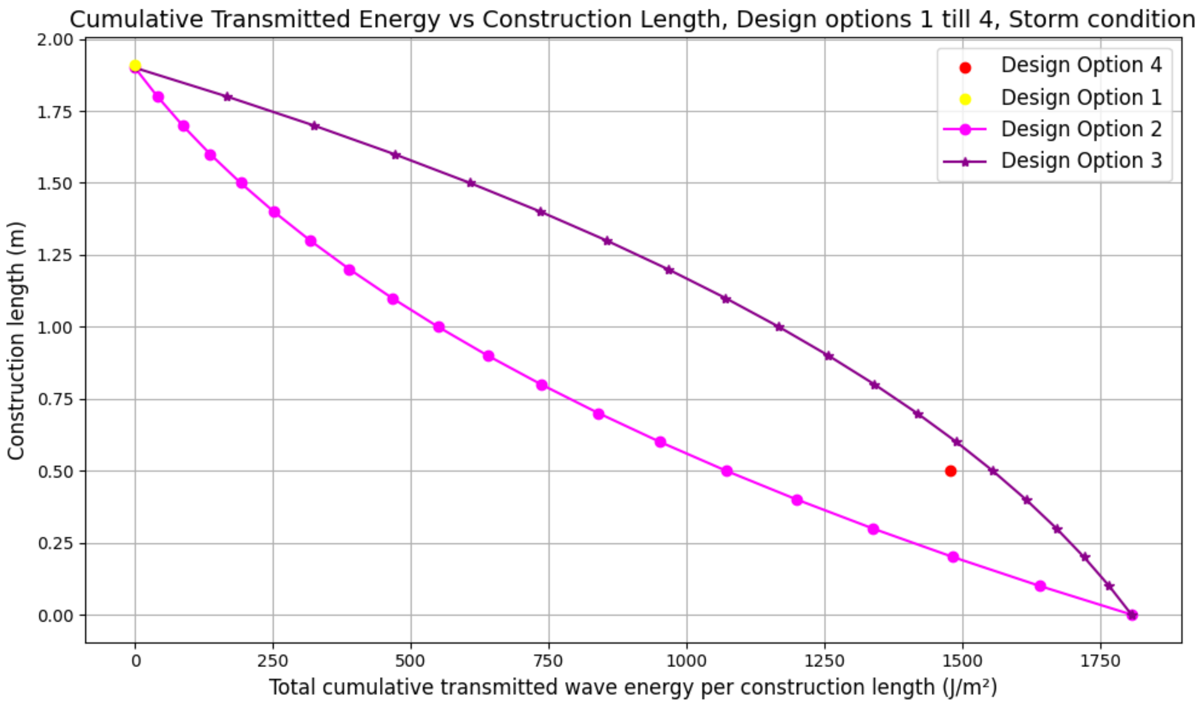

Figure 25: Overview of the total cumulative transmitted energy (J/m^2) (on the x-axis) generated by different construction heights (m) (on the y-axis) per Design Option for the storm condition.

Figure 26 shows the cumulative transmitted energy per construction height of Design Options 2 and 3 for the different water conditions (MLT, MSL, MHT and the storm condition). It is noticeable that at each water level Design Option 2, requires the least amount of construction height to achieve the same total cumulative transmitted wave energy as Design Option 3. This also demonstrates that Design Option 2 is the most optimal.

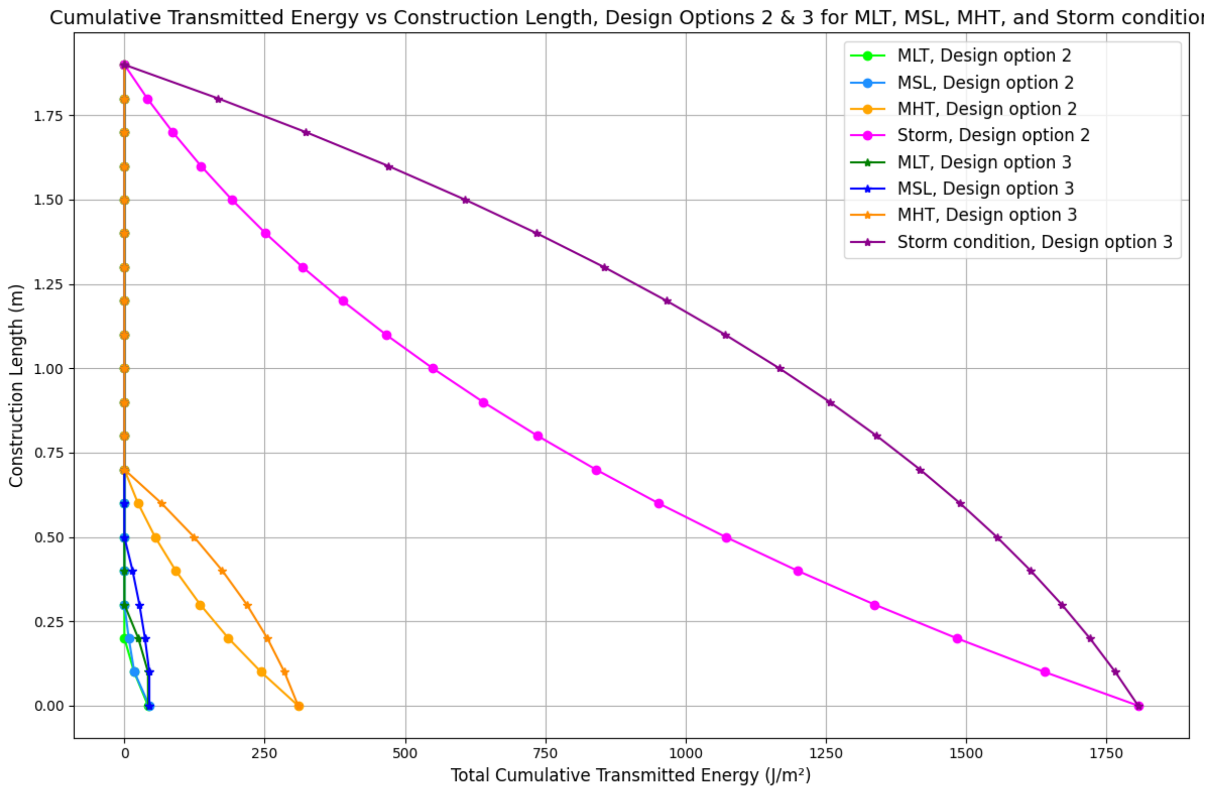

Figure 26: Overview of the total cumulative transmitted energy (J/m^2) (on the x-axis) generated by different construction heights (m) (on the y-axis) for Design Options 2 and 3 for all water conditions.

4.3. The critical wave energy for mangrove restoration

Based on the theory described in Chapter 3 of this report, the critical wave energy for mangrove establishment is calculated. While calculating the critical bed shear stress, the shear stress caused by flow is neglected. It is thus assumed that all bed shear stress is caused by waves. The bed shear stress caused by waves is mainly affected by the significant wave height and the water depth. Therefore, each modelled hydrodynamic condition has its own critical bed shear stress value. The water depth remains the same for the calculation of each critical bed shear stress. Therefore, only the significant wave height could be changed by the placement of horizontal elements into the water column. The critical bed shear stress, thus, corresponds to a critical significant wave height. This critically significant wave height is used to calculate a critical total wave energy.

The critical bed shear stress is calculated for mangroves of an age of 190, 220, 250, 280, 310, 340, 365, and 545 days. This is done for the worst-case scenario. The results show that the older the mangrove seedlings are, the larger the critical bed shear stress is. The critical bed shear stresses for mangroves, the variation in mangrove age, and for MSL, MHT, and MLT are shown in Figure 23. The results for mangrove seedlings of an age of 365 days are shown in Figure 24. The graphs corresponding to other mangrove ages are shown in Appendix G.

It is observed that the older the mangrove seedlings are, the greater the critical energy is. This critical wave energy varies by water level. Therefore, to enable mangrove restoration, the transmitted wave energy should not exceed the critical wave energy determined for that condition. It is also striking that at lower water levels, the differences between the critical energy for all ages are closer together than at higher water levels.

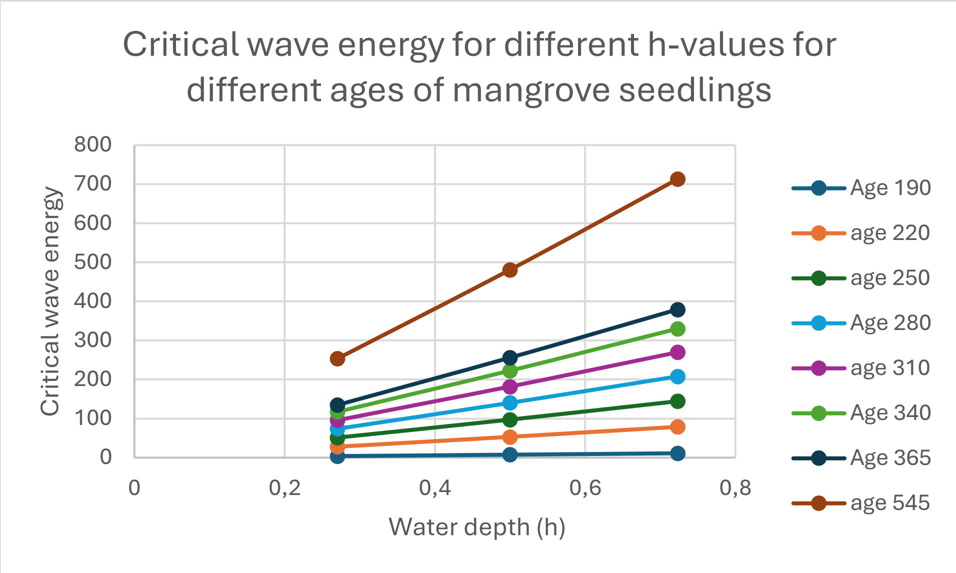

Figure 27: Overview of critical wave energy for different h-values for different ages of mangrove seedlings. The y-axis shows the critical wave energy in J/m², and the x-axis shows the water depth (h) in meters. Each seedling age has its color.

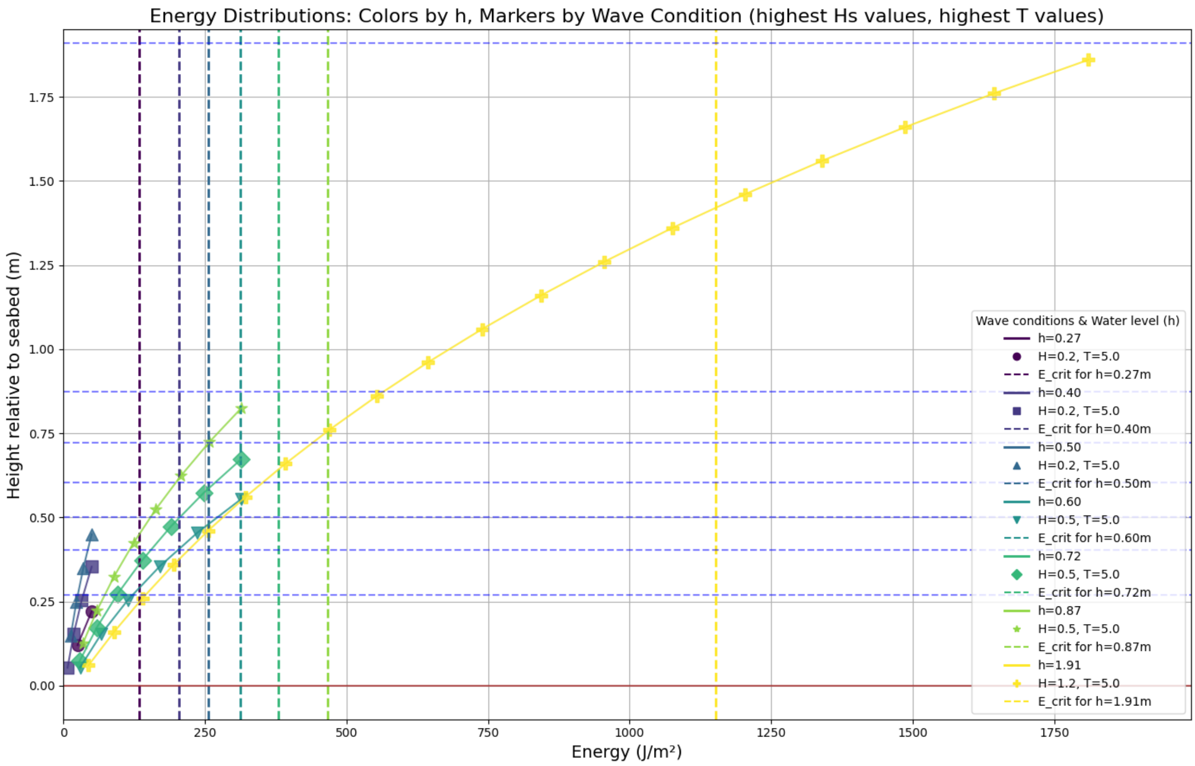

Figure 28: Total cumulative wave energy at 0.10 meter intervals in the water column for each water depth within the determined tidal range, AND the corresponding critical wave energy. The x-axis shows the wave energy in J/m², and the y-axis shows the height relative to the seabed. Each solid line represents the depth-specific wave energy at that height

relative to the seabed. The dark purple color represents the wave energy distribution for h=0.27. The dark blue, dark green, mint green, light green, and yellow lines represent the wave energy distribution of water depths of 0.50, 0.60, 0.72, 0.87, and 1.91, respectively. For each water depth, the worst-case scenario hydrodynamic conditions (highest possible wave period and wave height) are considered while calculating the total cumulative depth-specific wave energies.

The table below shows the critical energy values for mangroves at different ages per water depth condition: MLT, MSL, and MHT. These values are important for the determination of the required construction height.

4.4. Comparison between model output and wave flume experiment

The model output highly relies on the chosen reflection coefficient. To validate the chosen reflection coefficient, wave flume experiment data is used. For both the model output and the wave flume experiment results, the transmission factors, denoted as "Ct value," are compared to the construction height divided by the water depth (Figure 29). The scatter points represent the 'original' model outputs, with water depths of 0.20, 0.24, and 0.30 meters, significant wave heights of 0.08 and 0.09 meters, and wave periods of 1.16, 1.21, and 1.27 seconds.

The model output shows a trend that is similar to the one observed in the wave flume experiment. However, the model predicted that the transmission factors are lower than those gathered from the wave flume data. Conversely, the wave flume data may overestimate these factors relative to model predictions. This is likely the latter, as the wave flume results include transmission factors exceeding 1.0.

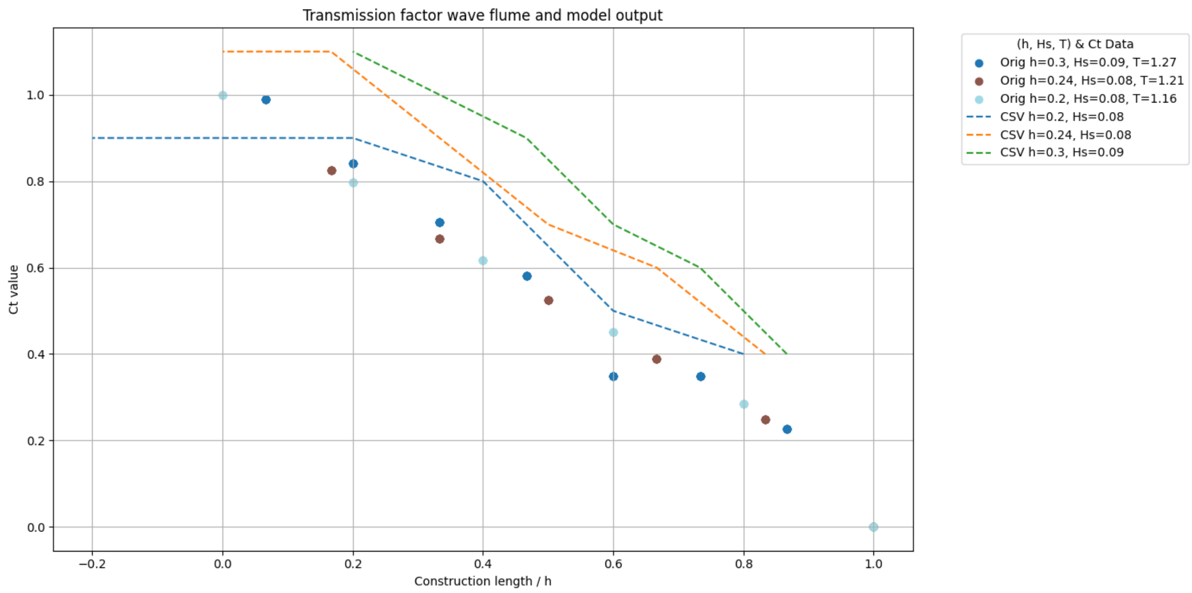

Figure 29: A comparison of the transmission factor predicted by the model and the transmission factors determined in the wave flume experiment. This is done for different water depths, wave heights, and wave periods.

The wave flume experiment conducted contains some inaccuracies, which complicate the thorough validation and calibration of the model using these experiments. These inaccuracies are mentioned in the Alinea below. Instead, to evaluate the reflection coefficients' impact on the transmission factor in the wave flume model, a sensitivity analysis is conducted.

First of all, the wave flume experiments lack data for the first step, where the structure entirely fills the water column. This absence accounts for the gap between a transmission factor of 0 and the starting point of the green, orange, and blue lines in Figure 25. This gap highlights the need for further investigation into the initial conditions of the experiments and adjustments in model calibration to improve alignment with experimental data. The experimental data shows some transmission factors which are exceeding 1.0. The measurements are thus most likely a overestimation of reality. This inconsistency might have occurred from inaccuracies in the experimental setup. A limitation in the experiment set-up is the inability to measure incoming and transmitted wave heights simultaneously. Another limitation is the lack of sufficient data points where the structure fills the water column. Observed differences between the model results and the results of wave flume experiments show that the model might not be accurate. However, the wave flume experiment results might also be incorrect. Therefore, additional wave flume experiments are recommended. The experimental data show some transmission factors that exceed 1.0. The measurements are thus most likely an overestimation of reality. This inconsistency might have occurred from inaccuracies in the experimental setup. A limitation in the experiment set-up is the inability to measure incoming and transmitted wave heights simultaneously. Another limitation is the lack of sufficient data points where the structure fills the water column.

4.5. Sensitivity analysis

For the sensitivity analysis, a comparison between the model output and the wave flume experiment results is made (Figure 30). This graph shows the variation of the transmission factor under different conditions and construction height to water depth ratios.

The graph demonstrates that the larger the construction height to water depth ratio is, the wider the spread of different transmission coefficients. For smaller structure length to water depth ratios, the transmission factors corresponding to various reflection coefficient values are more clustered. For the experiment results, this is the other way around. It could either be that the model, the experiment data, or both are inaccurate. This highlights that the model is more sensitive to changes in the reflection coefficient at larger structure length-to-length ratios. Highlighting the increasing influence of structure length on wave transmission as the structure length extends relative to the water depth.

In addition, a notable dip in the transmission coefficient occurs at a construction height-to-water depth ratio of 0.6. Interestingly, the transmission coefficient value at a ratio of 0.75 is equal to that at 0.6. To achieve a ratio of 0.6, the construction height must be 0.18. For a water depth of 0.30 m, this corresponds to a depth of 0.12 m. A ratio of 0.75 corresponds to a depth of 0.07 m. However, the model simulates depths in increments of 0.04 m, meaning that the nearest available construction depths are 0.08 m and

0.04 m, which are both shallower than 0.12 m. When analyzing the plot for Design Option 2, which applies wave flume conditions for a water depth of 0.30 m, several patterns emerge. The cumulative total transmitted energy decreases in the following order: -2.8, -2.1, -1.7, -2.2, 0, -0.7, -0.5 (Figure 30). At step 5, the energy drop is significantly larger than expected, causing the sudden dip in the transmission coefficient curve (Figure 30). At step 4, the cumulative energy does not decrease at all, resulting in no further transmission loss at that point. This explains why the transmission coefficient value at a ratio of 0.75 equals that at 0.6. This abrupt behavior is likely due to the model's resolution and stepwise handling of depth layers, and may indicate a discretization error in the simulation.

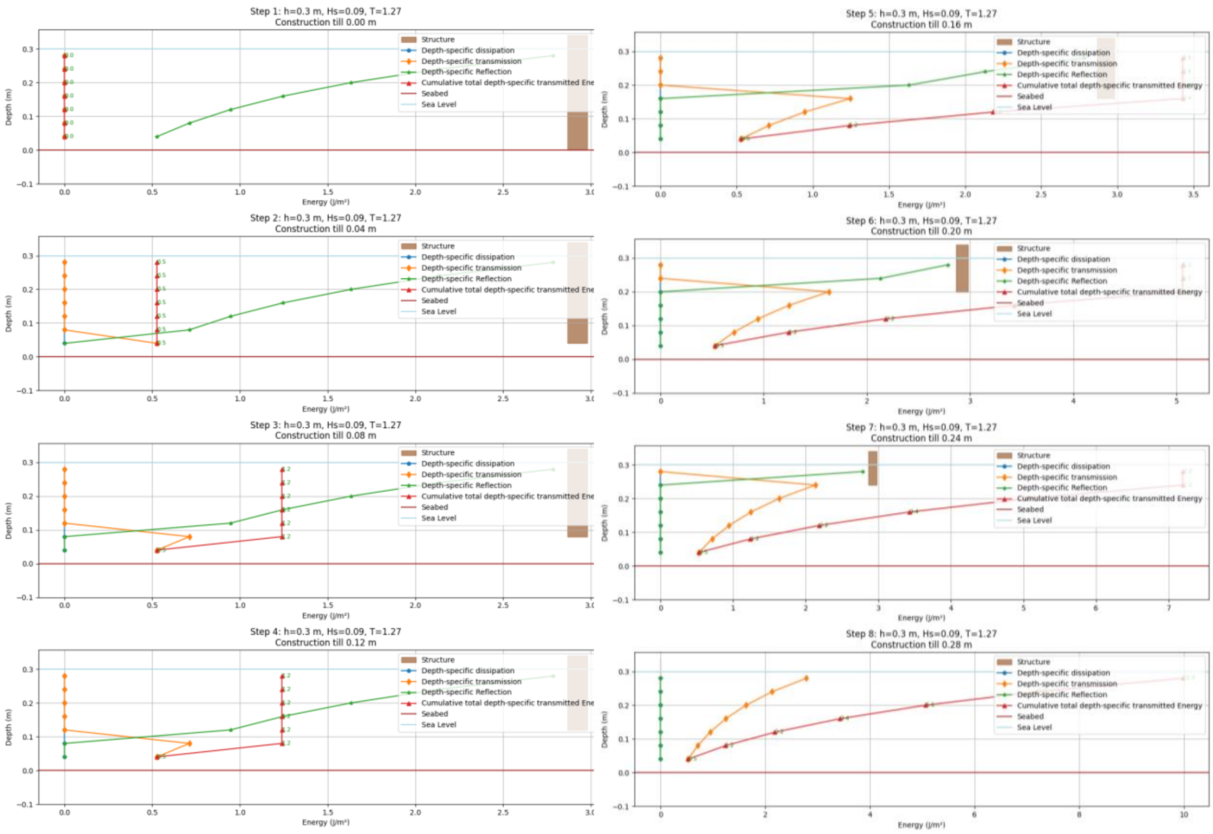

Figure 30: Simulation of step 2 under wave flume experiment conditions. The values of the total cumulative transmitted wave energy are also plotted.

It is imaginable that at the bottom edge of the structure, the last horizontal element or elements do not have a reflection coefficient of 1, but lower reflection coefficients. Further up in the structure, the reflection coefficient could go towards 1. In addition, the dissipation coefficient does not vary now. Besides the fact that energy reflects or transmits, energy will also dissipate. The values that the reflection, transmission, and dissipation coefficients should have will have to be derived from valid experiments.

Therefore, the sensitivity analysis underscores the importance of accurately defining the values to align model predictions with experimental observations. However, it is hard to calibrate the model using experiment outcomes that are most likely inaccurate.

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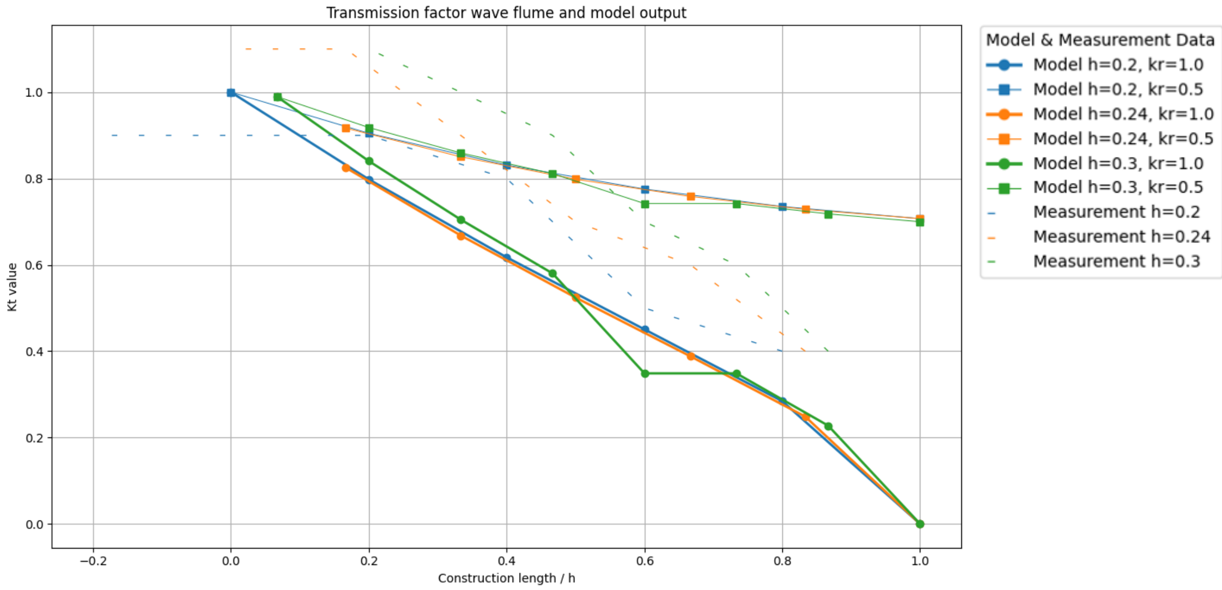

Figure 31: Comparison of model output and wave flume experiment data

A comparable graph is shown in Nortier & de Koning (1996). In this graph, the transmission factor (y-axis) is plotted against the construction height-to-water depth ratio (x-axis). This is done for different wave steepnesses. The wave steepnesses in the graph range between 0.10 and 0.70. For the model and wave flume experiments, wave steepnesses ranging from 0.010 to 0.040 were tested. The graph of Nortier & de Koning (1996) shows that the larger the wave steepness, the more hollow the line. For wave steepnesses smaller than 0.30, the lines become more convex. Assuming that for wave steepnesses below 0.10 the lines become even more convex. The model has a wave steepnesses of 0.10 and 0.12. Hence, more convex lines are expected for the model and wave experiment results. Such a trend is, however, not observed. The lines of the experiment results are likely shaped as the line in Nortier & de Koning (1996) that corresponds to a wave steepness of 0.30. The scatters plots, belonging to the model output, have a comparable shape.

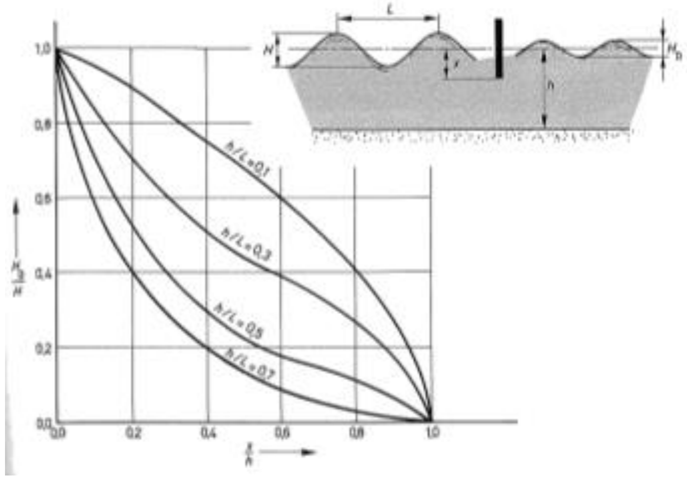

Figure 32: Graph Nortier & de Koning (1996) showing the transmission factor corresponding to different construction height water depth ratios for different wave steepness's

To analyze the extent to which the model matches Nortier & de Koning (1996) 's graph, the two graphs were superimposed. In this way, the wave steepness output of 0.10 and 0.30 from Nortier & de Koning (1996) is compared with a model that uses this wave steepness as input. This resulted in Figure 33. The model here uses different reflection coefficients. This analysis shows that the model with a wave steepness of 0.30 (h=0.5, Hs=0.167, T=0.3) and a reflection coefficient of 1.0 is fairly similar in shape to the shape of the line in N's graph. However, for this condition, the line is closer to the line in Nortier & de Koning (1996), at a reflection coefficient of 0.9. In this case, however, from a construction height/h value onwards, the shape of the line is different from that in Nortier & de Koning (1996). At a wave steepness of 0.1, the model does not come close to the line in Nortier. Also, the shape of the line generated by the model differs from the shape in Nortier. However, at a reflection coefficient of 0.8, the line in Nortier & de Koning (1996) is met. Thus, the model does not quite match what is described in the literature. This could be because, for example, the model uses a dissipation coefficient of 0. This means energy is either reflected or transmitted, and the sum of the transmitted and reflected wave energy is always 1. This is not the case in reality.

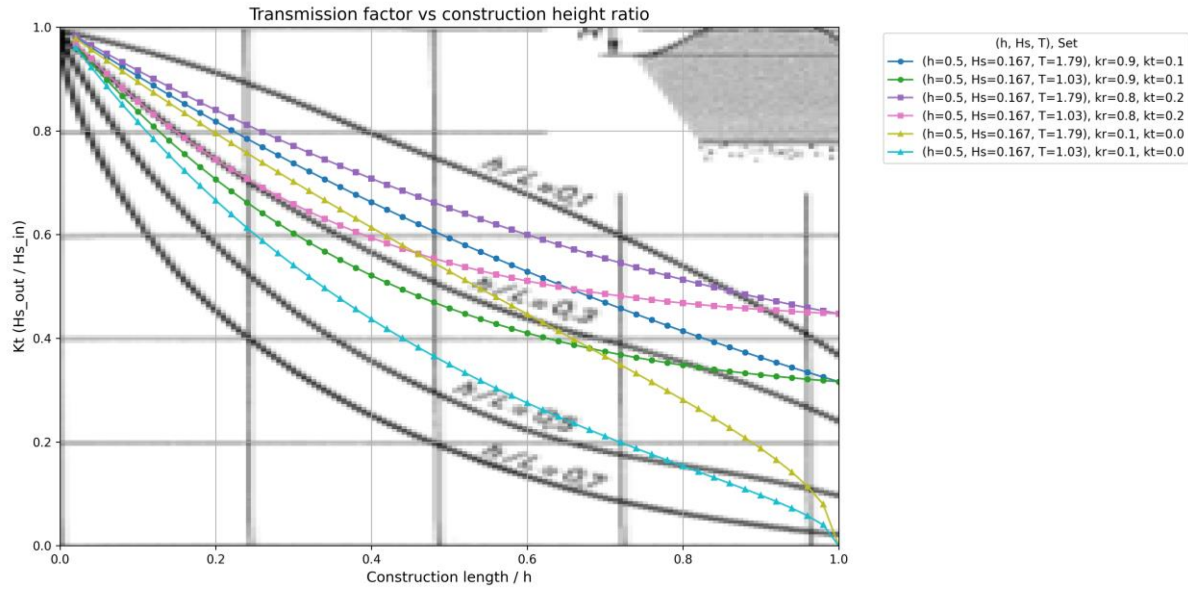

Figure 33: Comparison of Nortier & de Koning (1996) *and model results. The graph of* Nortier & de Koning (1996) *shows the construction height- to water depth - ratio for wave steepnesses of 0.1, 0.30 , 0.5 and 0.7.*

4.6. The optimum vertical placement relative to the water level of the horizontal bamboo beams

From section 4.3.5, Design Option 2 seems to be the most “optimal” design option. To say this with certainty, two more analyses were performed.

In the first analysis (Figure 34), the required construction heights and corresponding positioning of Design Options 2, 3, and 4 are shown for each water level (MLT, MSL, MHT, and the storm condition). This shows which Design Option requires the least construction height and where there is overlap between the structures. For all water conditions, it can be concluded that Design Option 2 requires the least construction height. However, this is not the case for seedlings 190 days old, where Design Option 2 and 3 require the same construction height and positioning. Design Option 4 only suffices for MSL and MHT from a seedling age of 220 days. For MHT, the required construction height of Design Option 2 at this age is the same as the required construction height for Design Option 4. For MLT, Design Option 4 satisfies only from 250 days. For the storm condition, this is only from mangrove seedlings older than 365 days.

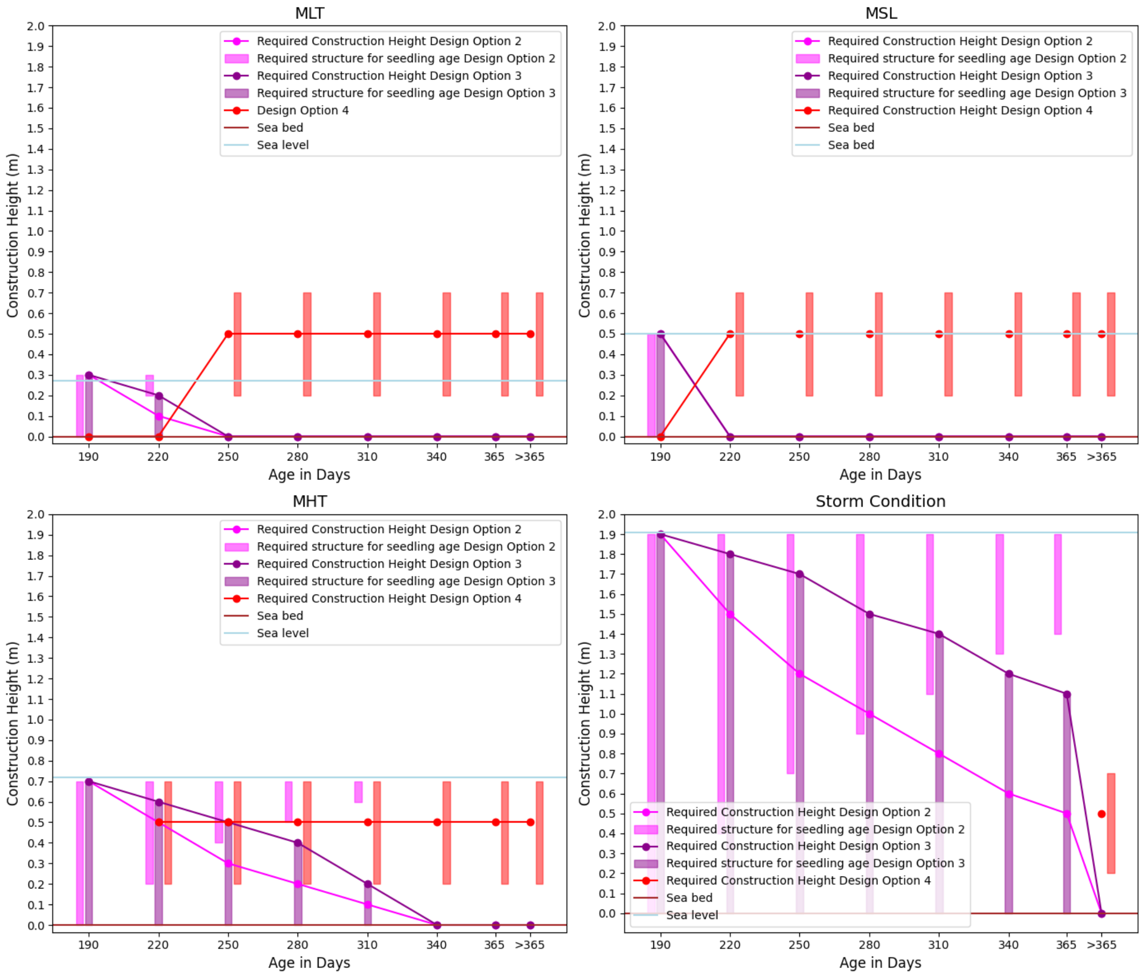

Figure 34: The required construction heights (plotted as lines) and corresponding positioning (plotted as bars) of Design Options 2, 3, and 4 are shown for each water level (MLT, MSL, MHT, and the storm condition).

From all considered designs, design option 2 is the most efficient design option (when considering structures which are no higher than the water level). For all water levels and mangrove ages, this design option requires the least amount of material to meet the critical wave energy. The construction height required to meet the critical energy associated with an age varies by water level. The storm conditions require a much larger construction than the other water levels. It depends on the requirements set for a project, which water level needs to be taken into account. Furthermore, it depends on the age of the mangroves present, how much material is needed.

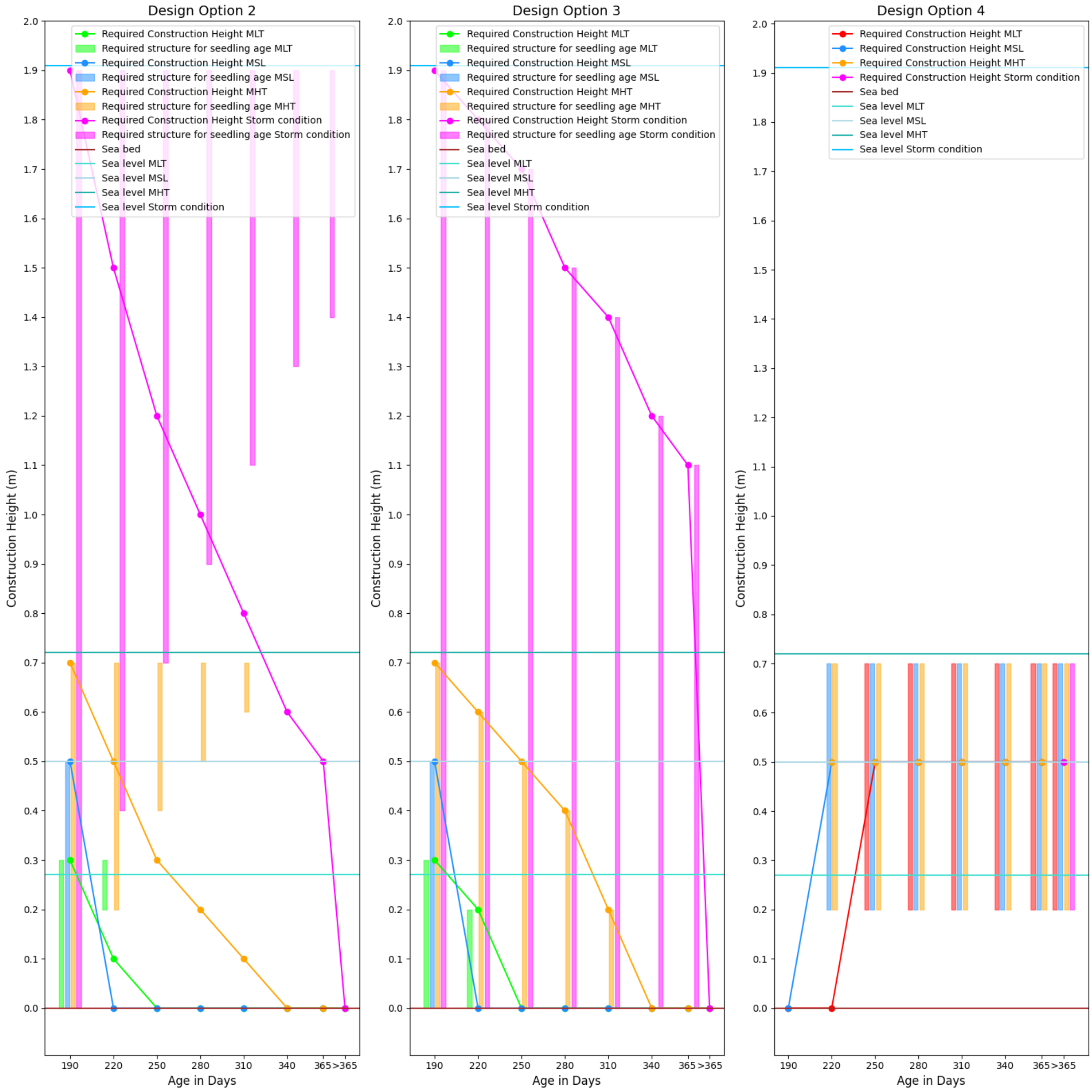

Figure 35: The required construction heights (plotted as lines) and corresponding positioning (plotted as bars) of Design Options 2, 3, and 4. Per design Option the different water depth scenarios are simulated.

In the second analysis (Figure 35), for each Design Option (2, 3, and 4), the required construction heights and positioning for different water levels (MLT, MSL, MHT and storm condition) for different mangrove seedling ages are shown. From this, it can be seen at a glance that Design Option 2 requires a lesser construction height for the different mangrove seedling ages.

5. Expert elicitation

To explore the limitations of the current design method and the benefit and applicability of a model to generate an optimal design an expert elicitation is performed. The answers given in the Expert Elicitation are shown in Appendix H. The outcomes of the elicitation help in formulating an answer to three sub questions that are needed to give an answer to SQ6.

SQ6.1: What are the limitations of the current design method of permeable structures used for mangrove restoration projects?

The expert elicitation gave several insights. One of these insights is an overview of the most important limitations of the current design method for permeable structures used for mangrove restoration. These limitations are listed below.

1. **Lack of Standardized Guidelines:** Practitioners mentioned the absence of detailed design guidelines. According to experts in the field, this leads to ad hoc approaches based on local conditions and available materials.
2. **Trial-and-Error Approach:** The current design process is, by most experts, described as trial-and-error and expert judgment. Both approaches cause inefficiency in the designing phase and the final design of the permeable structures.
3. **Limited Data Implementation:** Data on environmental conditions, such as wave heights, tidal ranges, and sediment transport, are currently often not used to design the dimensions of permeable structures. The designs are thus not as efficient as possible. Implementing these location-specific data in designing the dimensions of the permeable structure could increase the design effectiveness.
4. **Effectiveness and Longevity:** The current designs may not provide sufficient longevity or effectiveness. This is mentioned by most of the experts.

SQ6.2: What are the limitations of using the model generated in this thesis for the design of permeable structures used for mangrove restoration?

The model developed in the thesis may face several limitations, as identified by the experts:

1. **Simplifications and Assumptions:** The model makes several assumptions. One of these assumptions is that waves approach the structure perpendicular. Experts mentioned this to be a good simplification. This way, the worst-case scenario is assumed. Currents are not considered. One of the experts mentioned that this could have the risk of skipping the inundation period. Two other experts mentioned currents and especially the tide need to be considered. Other experts, however, mentioned that leaving currents out is fine. It was mentioned that currents influence the water levels. However, according to the

experts, most assumptions and simplifications are appropriate for the goal of this model.

2. **Not including sediment transport:** Almost all experts mentioned that sediment transport should be included in the model to determine the success of the simulated structures.
3. **Absence of Stability Analysis:** Almost all experts mentioned that a stability analysis should be included in a model. This way, a structure that is also stable will be chosen. When leaving a stability analysis out, the chosen structure could be unstable.

SQ6.3: What factors/elements increase the likelihood of experts using the model for their research or design regarding permeable structures used for mangrove restoration projects?

Experts identified several factors that could enhance the likelihood of using the model:

1. **Ease of Use:** The model should be user-friendly, allowing easy input of data such as tidal ranges, wave conditions, and site-specific conditions, and the model should be fast. This is mentioned by almost all experts.
2. **Low Data Requirements:** Most of the experts mentioned that minimizing the need for extensive local data inputs can increase the model's practical applicability.
3. **Clear Visuals:** T. Wilms mentioned that clear visuals allow easy comparison of different design options could improve usability and decision-making.
4. **Digitalization:** One expert mentioned implementing the model in a GIS environment. One could then ‘click’ a location on the world map, and a model output should pop up there. This would simplify site selection for permeable structures used for mangrove restoration. It will also allow the overall design process to be made more efficient.
5. **Local Variability:** If the model does not account for local variability or practical challenges, its effectiveness and applicability may be limited. Open-source data should be used as model input to make the model applicable all over the world. This is mentioned by two on-site experts, mentioned that the use of locally available data and systems would increase the applicability of the model.
6. **Morphodynamical processes:** A. Astra mentioned that including that the model should demonstrate successful sediment trapping and address erosion challenges.

6. Discussion

The designed analytic model allows for a simulation of the wave energy distribution across varying depths in the water column and can serve as a tool to estimate the effectiveness of structures. However, the analytical model presented is a starting point, and there are some areas of improvement to be aware of before putting the model into practice. This section addresses weaknesses and inaccuracies in the model and the research conducted.

6.1. Uncertainties in the wave energy simulation

The developed analytical wave model serves as an efficient tool for simulating wave energy distributions over the depth of the water column. The simulation of depth-specific wave energy across the water column appears to be a new development. To what extent the simulated depth-specific wave energy corresponds to the actual amount of energy at various depths caused by waves in these conditions has not been verified. The model output shows that the energy from the seabed to the water surface increases. Since water particles make greater movements as they get closer to the surface, the energy towards the water surface should logically increase as well.

In contrast, energy distribution runs only from the seabed to the water surface. In reality, the amplitude of the wave also contains an amount of energy. However, the wave height and hence amplitude are included in the wave energy calculations. However, the simulation stops at the water surface. The simulation of the part above the water surface might be interesting for a follow-up study.

However, this model has faster computation times compared to numerical models, which is crucial for design optimization.

6.2. Uncertainty in the reflection, transmission, and dissipation coefficients

It became clear in Chapter 4 that the model deviates from both the measurement results and the graph in Nortier & de Koning (1996). On the one hand, the differences could be a deviation from the measurement results, but could also be caused by inaccuracies in the model.

The input parameters are the foundation of the analytical wave model. These parameters include e.g. wave heights, wave periods, water levels, reflection coefficients, transmission coefficients, and dissipation coefficients. When parameters are incorrectly chosen, the calculated wave energy over the water column is also incorrect. The reflection coefficient is based on the theory mentioned in Gijón Mancheño et al. (2021a). The model outcome is highly based on this constant reflection coefficient. Therefore, the impact of the horizontal elements on approaching waves may be oversimplified.

In reality, part of the incoming wave energy will be dissipated. Accordingly to Shu et al. (2023), the transmission, reflection, and dissipation coefficients are calculated using equations 41, 42, and 43

$$\frac{E_r}{E_i} + \frac{E_t}{E_i} + \frac{E_d}{E_i} = 1 \tag{41}$$

$$\left(\frac{H_r}{H_s}\right)^2 + \left(\frac{E_t}{H_s}\right)^2 + \frac{E_d}{E_i} = 1 \tag{42}$$

$$(K_t)^2 + (K_r)^2 + (K_d)^2 = 1 \tag{43}$$

where, K_t, K_r, and K_d are the transmission, reflection, and dissipation coefficients (Shu et al., 2023). In principle, it equals the energy of a wave, the square root of the wave height. Therefore, a transmission and reflection coefficient of a wave can be calculated as the reflected or transmitted wave height - by the incoming wave height ratio. The dissipated wave energy can be calculated as the square root of the ratio of the dissipated energy and the incoming energy. So these are different transmission, reflection, and dissipation coefficients from those used earlier in this study. In the performance of this study, these factors were not squared, but applied directly as a kind of percentage to the energies located at depths in the water column.

In this study, a porosity of 0 was used, which corresponds to a reflection coefficient of 1, and the transmission coefficient is equal to 0. Dissipation is disregarded and is also 0. The square of these factors used would be equal to the factor itself. As a result, it does not matter that the equations in Shu et al. (2023)have not been taken into account.

In reality, bamboo is a natural product and therefore not completely straight. As a result, it is unlikely that porosity would equal 0. In a study conducted by Lin & Karunarathna (2007).The effect of porosity on the reflection, transmission, and dissipation coefficients was investigated, and Figure 36 was created. It takes into account that the construction height (in the x-direction) (a) divided by the water depth should be equal to 2. In addition, a d_{50}/h of 0.02 is taken into account. This means that the element diameter should be equal to 0.01 m. The construction height (x-direction) should be equal to 1 m. Figure 36 is used to test the influence of other factors K_t, K_r, and K_d values using the equation with Nortier and de Koning. This will be done for porosities of 0.10, 0.20, and 0.60. These will be used in the equations described in Shu et al. (2023).

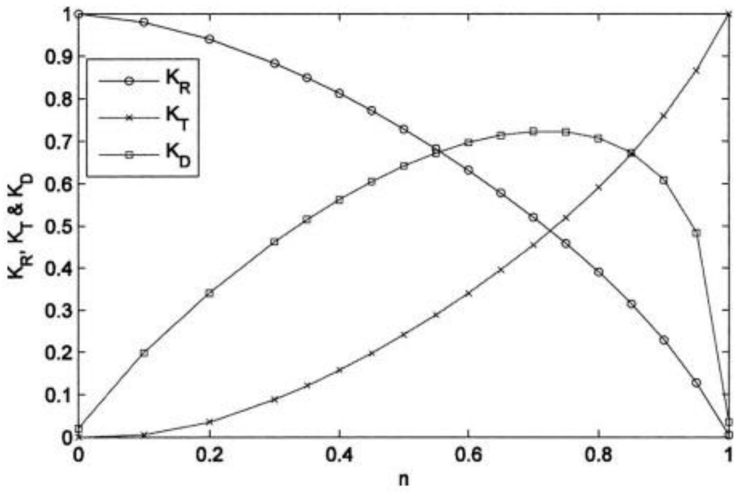

Figure 36: Different transmission, reflection and dissipation coefficients under different porosities (Lin & Karunarathna, 2007)

For a porosity of 0.10, ${K_r}^2$ equals 0.98², ${K_d}^2$ equals 0.20² and ${K_t}^2$ is practically 0. For a porosity of 0.20, ${K_r}^2$ equals 0.90, ${K_d}^2$ equals 0.10 and ${K_t}^2$ equals 0.0. For a porosity, ${K_r}^2$ equals 0.41, ${K_d}^2$ equals 0.49 and ${K_t}^2$ equals 0.10. These values were implemented in the model to compare the model output with theory.

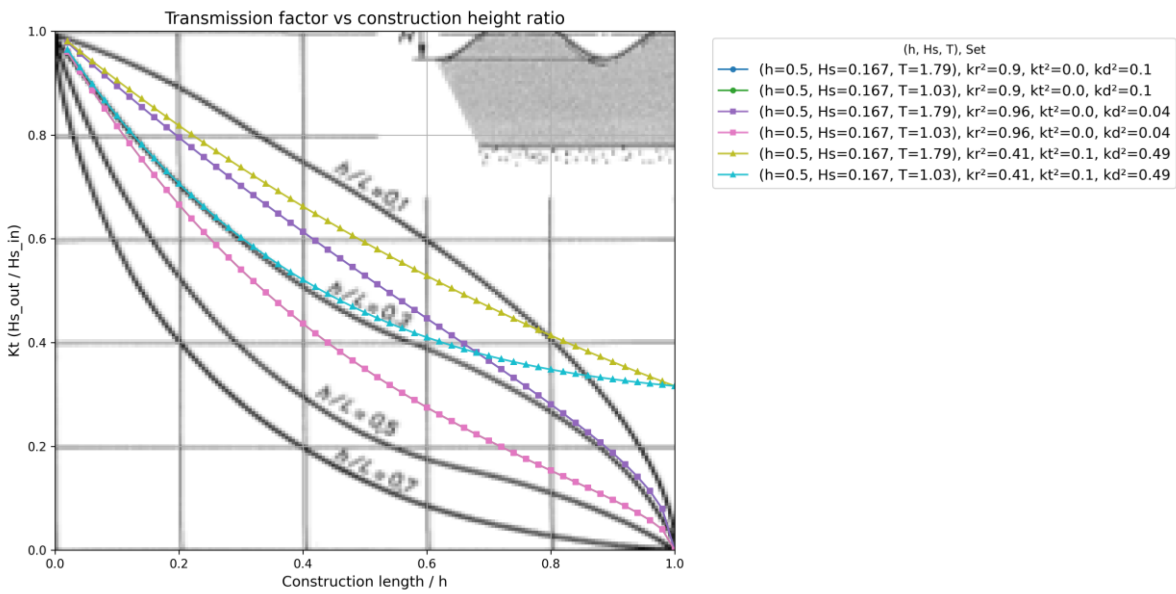

Figure 37: Comparison of model results under applied transmission, reflection, and dissipation coefficients to Nortier & de Koning (1996)

It is notable that for both wave steepnesses, the results where ${K_r}^2$ equals 0.90 and 0.96 yield a similar outcome. The best fit for a wave steepness of 0.30 ($T = 1.03$) seems to be for a reflection coefficient of 0.64, a transmission coefficient of 0.33, and a dissipation coefficient of 0.70. However, from a construction height to water depth ratio of 0.40, the transmission coefficient does deviate from the theory in Nortier & de Koning (1996). In addition, the transmission coefficient should decrease with increasing construction height to water depth ratio. However, this does not happen in the model.

So in the model, the transmission coefficient should decrease gradually as the structure height increases. This should make the model results closer to Nortier & de Koning (1996) theory. This is something that could be investigated in subsequent research. At these coefficients, the model is also not quite close to a wave steepness of 0.10 ($T = 1.79$). Perhaps at a different wave steepness, different coefficients apply, so the shape of the Kt-value graph for different wave steepnesses is also different from each other. Again, this is something for subsequent research.

6.3. Assumptions

Assumptions, such as assuming only waves occur and leaving tides and currents out, risk oversimplifying the complex dynamics of the wave propagation. Not taking currents and tides into account was mentioned to be risky by A. Astra, A. Reniers, and E. Horstman. Furthermore, the research only considers wave-induced shear stress for mangrove survival. Although this is expected to be the primary driver, other environmental influences are not considered. E.g., the presence of shipworm was also mentioned during the expert elicitation to influence the longevity of the structures used in mangrove restoration. Lewis (2005) mentions that the depth, duration, the frequency of flooding, soil saturation, and tidal inundation are important for mangrove growth and survival. Lewis (2005) also mentioned that salinity and free sulfide availability are threats to mangroves.

In the created model, the morphodynamic processes are not taken into account. The same goes for the stability of the structure. To make mangrove restoration possible, the sediment balance must be restored. Since the morphodynamic processes are not taken into account, it cannot be concluded whether the mangroves will be restored or not. Furthermore, the structure must be stable and resistant to the hydrodynamic forces working on it. Since the stability of the structure is not analysed, it cannot be concluded whether the structure can withstand the forces. This was mentioned by almost all experts questioned in the expert elicitation. To make the model applicable in the field, the stability and morphodynamic processes also need to be taken into account in the model. Only then, an accurate optimum design be chosen.

6.4. Critical wave energy

The calculation of critical wave energy for mangrove restoration is an important part of this study. The results suggest that older mangrove seedlings can withstand greater wave energy. A potential strategy for mangrove restoration could be to consider the age and developmental stage of mangroves. However, the calculated critical wave energy is highly based on the parameter values mentioned in Gijsman et al. (2024) and Balke et al. (2011). These values belong to *Avicennia Alba* Bl. seedlings of an age of 190, 220, 250, 280, 310, 340, 365, and 545 days.

In addition to the critical energy that different ages of mangrove seedlings can withstand, there is also a critical energy for sediment deposition. As mentioned earlier, sediment deposition and restoring the sediment balance are an important part of mangrove restoration projects (Wilms et al., 2020; J. C. Winterwerp et al., 2020). This again depends on a critical shear stress. The critical shear stress for sediment deposition is 1000 m / m² (Gijsman et al., 2024; Vundavilli et al., 2021). This critical shear stress is entered in the model. The critical energy associated with this critical shear stress related to sediment deposition, for different water conditions, is shown in Figure 37. For all conditions, the critical energy for sediment deposition is not exceeded by the simulated total wave energy. For sediment deposition to take place, based on the existing wave energy, no structure would need to be placed.

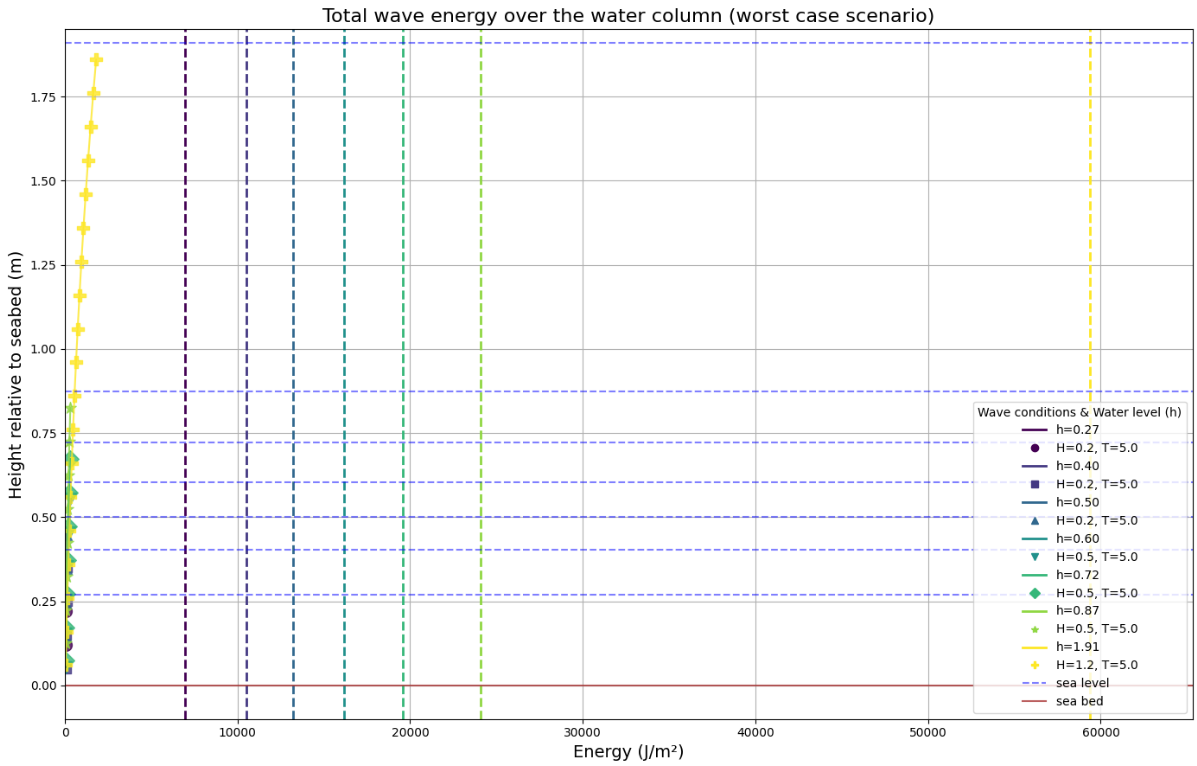

Figure 38: Overview of the critical wave energy, related to the critical bed shear stress for sediment deposition, together with the simulated cumulative total wave energy

However, this says nothing about the critical bed shear stress for erosion. This is based on a lower critical bed shear stress (0.50 N/m²) (Vundavilli et al., 2021). The simulated total wave energy for all water conditions is greater than the critical wave energy for erosion (Figure 38). Figure 38 provides a detailed examination of a specific section of the graph, revealing that even at the depth characterized by the lowest wave energies across different water levels, the energy present still exceeds the critical erosion threshold. However, the extent to which the amount of sediment deposition exceeds the amount of erosion and thus net sedimentation will occur cannot be deduced from this study.

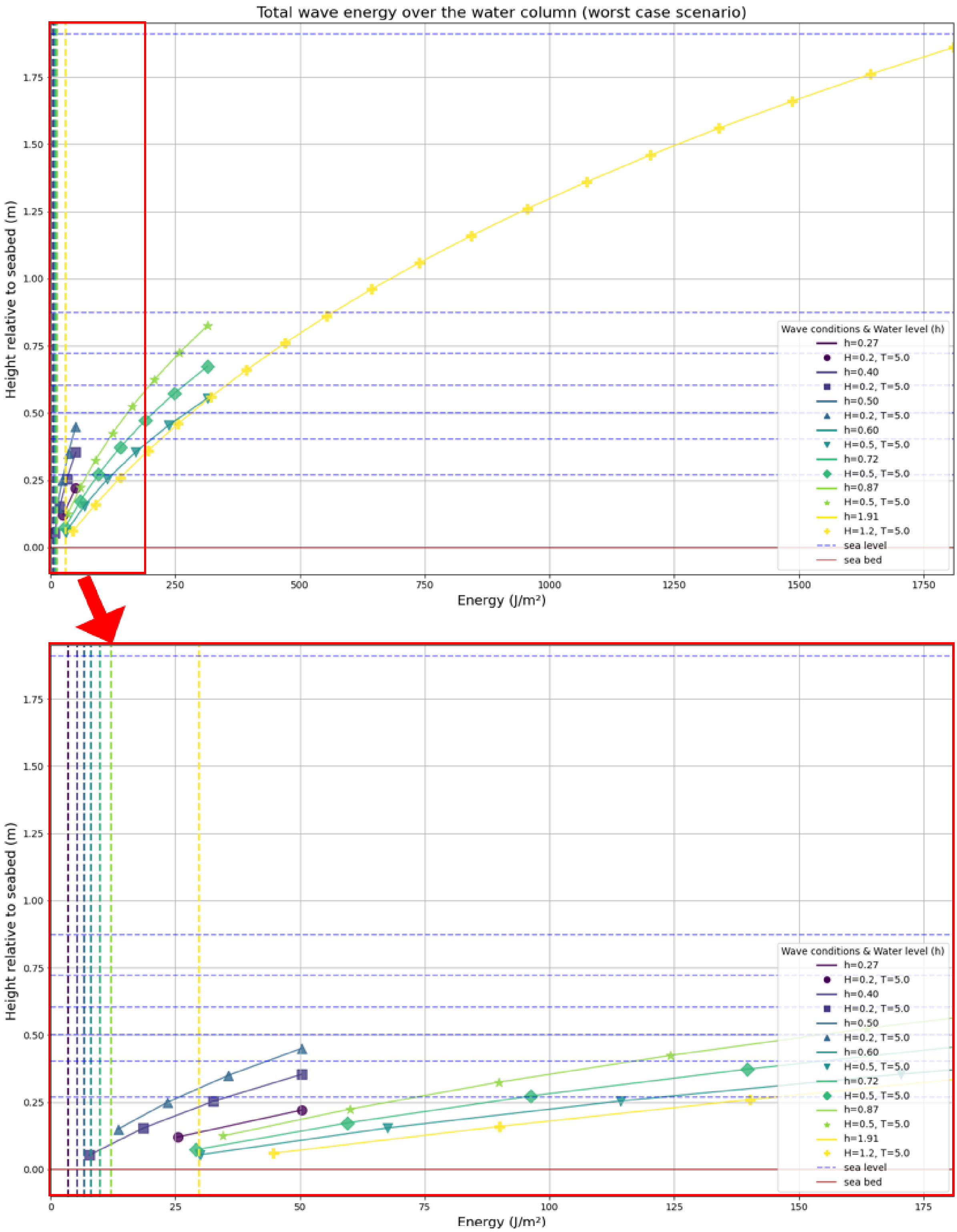

Figure 39: Overview of the critical wave energy, related to the critical bed shear stress for erosion, together with the simulated cumulative total wave energy

7. Conclusion

7.1. Wave energy simulation by an analytical wave model

SQ1. How can the depth-variable wave energy in (inter)tidal areas for different wave conditions and water depths be quantified by an analytical wave model?

The created analytical model predicts the energy distribution over the water column in an intertidal area in height intervals of 0.10 meters. The energy distribution is influenced by the significant wave height, wave period, and water depth. The significant wave heights and tidal ranges are extracted from open-source data.

The model predicts that most of the wave energy is located near the water surface. The wave energy decreases towards the seabed. This is in agreement with the existing literature that describes water particles having smaller movements closer to the seabed. The horizontal plates, which are placed closer to the water surface, block more wave energy. Since the model is based on open-source data, the model can be applied globally. Furthermore, due to its fast computation times, the model is useful for optimization purposes.

It should be noted that to what extent the simulated depth-specific wave energy corresponds to the actual amount of energy at various depths caused by waves in these conditions has not been verified. In contrast, energy distribution runs only from the seabed to the water surface. In reality, the amplitude of the wave also contains an amount of energy. Despite the amplitude being taken into account while computing the calculations, it would have been interesting to simulate the wave energy distribution from the seabed to the top of the wave.

7.2. The impact of varying design on the wave dynamics

SQ2. How can the impact of different design options for permeable structures on the depth-variable wave energy be implemented into this model??

Since the bamboo plates will be 0.10 meters, the analytical wave model already aids their strategic placement. Four design options were systematically modelled to simulate their impact on hydrodynamic conditions. The output from the analytical wave model is used again in the models simulating the different design options. The design options were simulated as reflection, transmission, and dissipation coefficients multiplied by the energy at specific depths, as computed earlier in the research.

As described in Chapter 3, the horizontal elements in the structure are simulated with a reflection coefficient of 1. At the depths where the structure is present, the corresponding energy is multiplied by the reflection coefficient of 1, the transmission coefficient of 0, and the dissipation coefficient of 0. Where no structure is present, the corresponding energy is multiplied by the reflection coefficient of 0, the transmission coefficient of 1, and the dissipation coefficient of 0. For each depth, the corresponding cumulative transmitted energy was calculated.

Design option 1 introduced a closed structure with no gaps between the horizontal elements, leading to complete reflection of wave energy due to a high reflection coefficient. Design option 2 introduced openings between the horizontal plates and the seabed, allowing for incremental energy transmission at different depths. Design option 3 involved varying the height of bamboo plates relative to the water level, effectively creating an inverse effect compared to design option 2. Finally, design option 4 simulated a practical solution based on expert judgment, focusing on bamboo beams placed between high and low sea water levels. A design option with gaps in between the horizontal elements is not tested in this study.

The model output is different from the wave flume experiment results. This could be due on the one hand to inaccuracies in the experiments, to inaccuracies in the model, or both. The latter is likely. In addition, a sensitivity analysis was performed for the reflection, transmission, and dissipation coefficients. Even with changes in the reflection and transmission coefficients, the model does not agree with the wave flume experiment data. When comparing the model output under different reflection, transmission, and dissipation coefficients with the literature, the model output deviates. A large deviation is caused because the transmission coefficient, if not equal to 0 for the elements, does not decrease to 0 as the construction height increases. As a result, for a water column that is filled by the structure, the transmission coefficient does not end at 0. According to the literature, this would make more sense.

7.3 The maximum allowed transmitted wave energy for mangrove restoration

SQ3. What is the maximum wave energy that corresponds to the maximum bed shear stress that mangrove seedlings can survive?

The maximum allowed transmitted wave energy for mangrove seedling establishment corresponds to the critical bed shear stress that seedlings can resist without dislodgement or erosion. This critical bed shear stress depends on seedling age, root length, and hydrodynamic conditions, and increases as the seedlings mature. Assuming the flow-induced stress is negligible, the total bed stress is based on the wave-induced stress alone.

The critical bed shear stress is used to calculate the critical wave energy. This is done for the worst-case wave conditions for MLT, MSL, MHT, and a storm condition. The critical energy for mangrove seedlings from 190 to 545 days, under MLT conditions, ranges between 4 and 254 J/m². For the same age range under MSL, the critical wave energy ranges between 7.6 and 481 J/m². For MHT, the critical wave energy ranges between 11 and 713 J/m². For storm conditions, the critical energy is by far the largest and even exceeds 1000 J/m².

The model does not include morphodynamic processes. However, the discussion did examine whether the simulated total cumulative wave energy exceeds the critical energy for sediment deposition. This is not the case for both MLT, MSL, MHT and the storm condition. The discussion also examines whether the cumulative total wave energy simulated by the model exceeds the critical energy for erosion. This is the case even just above the seabed for both MLT, MSL, MHT and the storm condition. The extent to which the amount of erosion is greater or less than sediment deposition has not been investigated.

7.4. 'Optimum' design of a structure

SQ4. For which structure design options can mangrove restoration/establishment be achieved while minimizing the number of horizontal elements?

The optimal design option that reduces the transmitted wave energy, allowing for mangrove restoration or establishment while minimizing the number of horizontal plates for all water levels and mangrove ages, except for an age of 190 days, is design option 2. This is the design option that fills the water column from the water level to the sea bed. This involves creating an opening between the seabed and the last horizontal element in the structure in 0.10-metre increments (the thickness of a horizontal element). However, design option 2 is the most efficient; a design with a specific construction height is not yet advised. Mainly, since this depends on project-specific requirements and location-based conditions, such as which hydrodynamic conditions are desirable to take into account. Furthermore, it depends on the age of the mangroves present, how high the structure has to be.

7.5. Limitations of the current design method and usability of the created model

SQ5. What are, according to experts within the field, the limitations of the current design method and the benefits and applicability of a model?

The current design methods for permeable structures in mangrove restoration lack standardization, rely heavily on a trial-and-error approach, and expert judgement. It is also mentioned that there are material resilience problems that affect the effectiveness and longevity of permeable structures. The model developed in the thesis addresses some of these limitations by providing a more structured approach for designing a permeable structure. Furthermore, the model is based on relatively simple calculations that approximate a design suggestion of this type of structure that could be well understood by experts in the field. Although the model must overcome challenges related to assumptions, data requirements, and usability. Its applicability will increase by integration with existing systems, and clear visuals, making it a promising tool for future research and design projects in mangrove restoration.

Very interesting was the suggestion of implementing the model in a GIS environment. One could then 'click' a location on the world map, and a model output should pop up there. This would simplify site selection for permeable structures used for mangrove restoration. It will also allow the overall design process to be made more efficient. Using open-source data as input for the model would make the model suitable for such digitalization. For the model to indeed calculate a design after clicking on a location on the world map, however, the conditions the structure must meet would have to be defined. These include the age of the mangroves and the minimum wave and water level conditions.

7.6. Main research outcome

To what extent can the design of permeable structures used in mangrove restoration projects be optimized using a model that computes the depth-variable wave energy transmission of different design options?

The optimization of permeable structures for mangrove restoration can be improved using the developed model that simulates depth-variable wave energy transmission across different design options. The model created in this study is a good first step towards such a model. The model is using open-source data as input data, which allows the model to be used for projects at various locations across the globe. Furthermore, the model has fast computation times.

Design option 2, which introduced openings between the horizontal plates and the seabed, meets the critical wave energy while containing the least amount of material. Therefore, Design Option 2 is the optimum design. However, a specific design is not recommended, since it depends on project-specific conditions, such as the water levels and wave conditions that apply and the mangrove seedling ages to be faced.

There are a number of shortcomings in the current model. Firstly, the model should be extended by adding morphodynamic processes, a stability analysis, and project-specific requirements. In addition, the model currently has no construction height varying transmission factor and therefore differs from Nortier. Also, the model could not be calibrated using a wave flume experiment.

To make the model more applicable in practice, a number of improvements and more in-depth analyses will have to be made in follow-up studies.

8. Recommendations for further research

The findings from this study provide a foundation for optimizing the design of permeable structures used in mangrove restoration projects. However, the model could be improved. Therefore, some recommendations for further research are given.

8.1. Validation and calibration

It is highly recommended to perform further validation and calibration of the reflection, dissipation, and transmission coefficients for various design options. Therefore, it is suggested to perform an additional wave flume experiment. In these wave flume experiments, the wave height in front of the structure and behind the structure should be measured at the same time. The measurement results could be used for model calibration. Furthermore, the model should contain a construction height variable transmission coefficient to meet Nortier & de Koning (1996).

8.2. Including the stability of the structure

The structure's stability is not examined. To ensure that the structure is stable, a module assessing structural stability should be added to the model. This was mentioned by almost all experts during the expert elicitation.

8.3. Including morphodynamic processes

Yet, the morphodynamic processes are not examined. Morphodynamic processes, however, have a great influence on mangrove establishments. Therefore, it is important to include those processes in the model. This was mentioned by almost all experts during the expert elicitation. This way, it can be concluded whether there is more sediment deposition than erosion.

8.4. Explore mangrove seedling parameters for different seedling ages and species

When determining the critical wave energy for mangrove seedlings, the model takes the parameters into account that correspond to *Avicennia Alba*. Bl. seedling of 365 days old. To make the model more reliable and more general, the parameters belonging to seedlings of other mangrove species and ages should be examined and added to the model.

8.5. GIS Integration and Digitalization

J. Noordermeer mentioned that the model in a GIS environment, as suggested by could simplify the design process. Future research should explore ways to integrate the model with GIS technology, allowing users to visualize potential outputs directly on a map. This would make site selection and design optimization more efficient. This improves the models' accessibility and ease of use.

8.6. Planting mangroves

In the case of planted mangrove seedlings, it is wise to do so during the S.E. monsoon season. As mentioned earlier, the S.E. monsoon season contains calm wave conditions. This S.E. monsoon season occurs between May and September. Since the wave conditions are calmer then, the mangroves need to withstand even less ‘heavy forces’. In the S.E. monsoon season, the mangroves’ roots can then already become larger and more robust. When the roots are long enough to withstand the hydrodynamic conditions, the mangrove seedlings will survive (Balke et al., 2011). The more the mangroves can withstand, the smaller the structure has to be. However, this optimum was not investigated in this study.

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"During the preparation of this work, I used Chat.WBT and OpenAI to improve writing quality of the report and debugging of the code. Furthermore, I used Chat.WBT and the transcription tool of Microsoft Teams and Witteveen+Bos for the reporting of the expert elicitation. After using this tool/service, I thoroughly reviewed and edited the content as needed, taking full responsibility for the final outcome."

Appendix A: Briefing Document Expert Elicitation for the benefit of the master thesis Green Protecting Green

Introduction

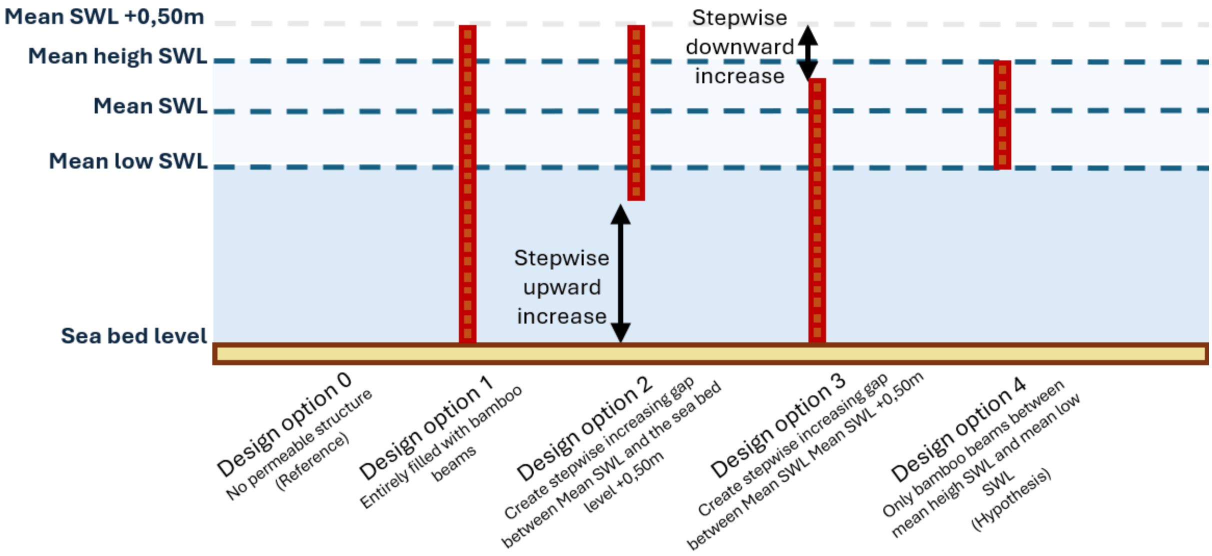
Introducing myself

My name is Dimphy Jacobs. I am 24 years old and currently conducting my Master Thesis at University of Twente to finish the master Integrated Water Engineering and Management. From Witteveen+Bos, I will be supervised by Tom Wilms. From UT, I will be supervised by Erik Horstman and Rutger Siemes.

Background information on the research

Mangrove forests provide essential coastal protection against waves, erosion, and storms. However, human activities have led to significant mangrove deforestation. There is a growing need for mangrove restoration. A way to make mangrove restoration possible is by placing permeable structures. Previously this has also been done in the Demak region in Indonesia. The permeable structures will reduce the incoming wave height and wave energy, so calm conditions that are suitable for mangrove restoration will be created.

The main objective of this research is to determine to what extent the design of permeable structures used in mangrove restoration projects can be optimized using a model that computes the depth-varying wave energy transmission, reflection and dissipation of different design options. An analytical model will be developed that calculates the total incoming wave energy and plots the wave energy distributions over the water depth. Next, the permeable structures will be implemented into the model. These simulate the permeable structures, represented as horizontal bamboo plates attached to vertical bamboo poles. Four design options with varying placement of the horizontal elements relative to the water level are simulated. For each design option its effect on the wave energy distribution and the resulted transmitted wave height is examined. The design options are also shown in the figure below.



An optimization will be conducted, to find the design that causes a certain transmitted wave height while using the least amount of material.

The expert elicitation

Purpose of the expert elicitation

The expert elicitation aims to gather qualitative insights from field experts regarding the current design methods for permeable structures used in mangrove restoration projects. The elicitation will also evaluate the potential benefits and applicability of a new analytical model designed to optimize these structures for enhanced wave energy dissipation and material efficiency. It should highlight the practical usefulness and applicability of this theoretical research and final product.

Objectives of the Expert Elicitation

1. Identify the limitations of current design methods for permeable structures in mangrove restoration.
2. Assess the potential benefits of using an analytical model for optimizing the design of permeable structures used in mangrove restoration within the working field.
3. Determine the characteristics that would make the model (more) useful for field applications.
4. Evaluate the likelihood of the model being adopted by experts in the field.

Scope and Format of Expert Elicitation

Participants: Experts in the field of permeable structures for mangrove restoration, including researchers, engineers, and on-site experts from organizations like Witteveen+Bos, Ecoshape, and the University of Twente.

Format: Semi-structured interviews with open-ended questions.

Appendix B: Known measurements for permeable structures

Element	What Measurement	Measurement in numbers
Entire permeable structure	Distance from the mangrove forest that it should be placed	165 meters
Vertical poles	How deep it has to be dug into the sea bottom	2.64 meters
	How much above the Mean Spring Water Level	0.50 meters
	Total length	4.64 meters
	Pole diameter	0.12-0.15 meters
	Distance between vertical poles, placed next to each other	0.60 meters
	Distance between vertical poles places behind each other	0.40 meters
Horizontal poles	Length	4 meters
	Pole diameter	0.10-0.15 meters
	Pole placement	Mean Water Level (if needed)
		Low Water Level
		High Water Level
Fill material	Diameter fill material	0.02-0.10 meters
	Length fill material branches	2 meters
	Placement top fill material branches	0.30 meters above High Spring Water Level

Appendix C: Determination of the hydrodynamic conditions

Predictions made by a model

Next to wave heights based on literature and measurements, a predictive model could be used to define the wave heights, wave periods and tidal spectrum.

Tide spectrum

To determine the amplitude of the tide, IHO data is used. This is approximate model data. Thus, the values for the tidal amplitude are also approximations. Nevertheless, the accuracy of this approximation is adequate to be used as input to the analytical model. Herein, the project location is given in a longitude and latitude value. The model then generated the tidal amplitude for a time period of 1 year. This is the period 4 October 2024 to 4 October 2025. The tidal amplitude is shown below in Figure 1.

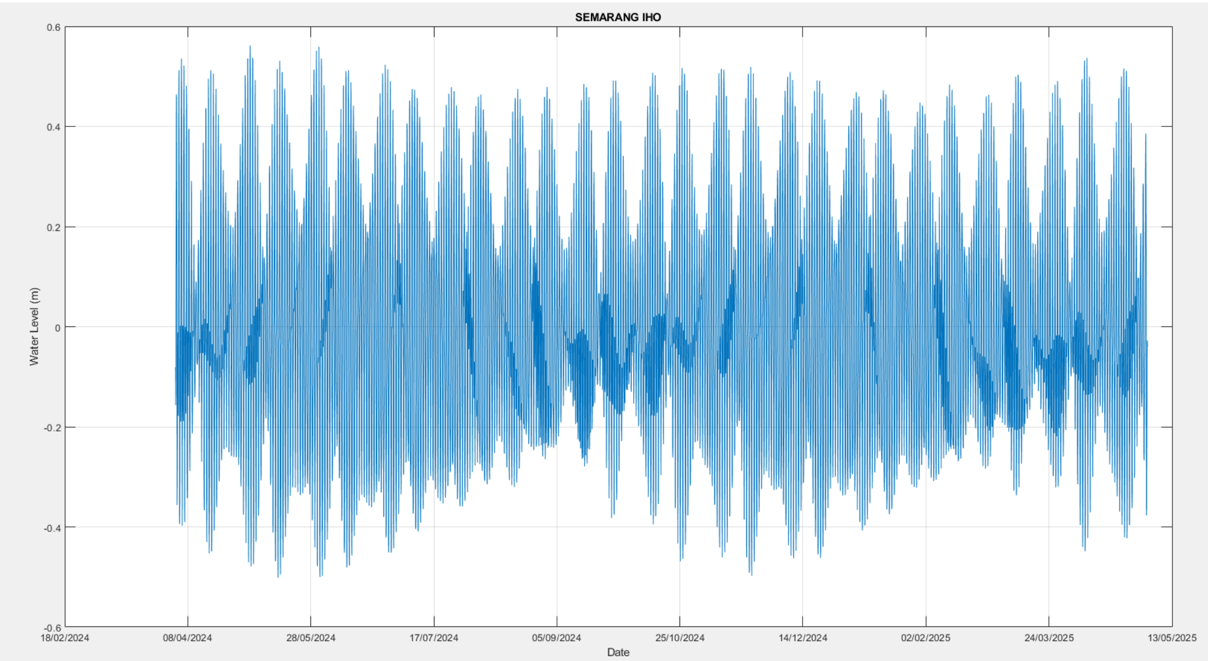
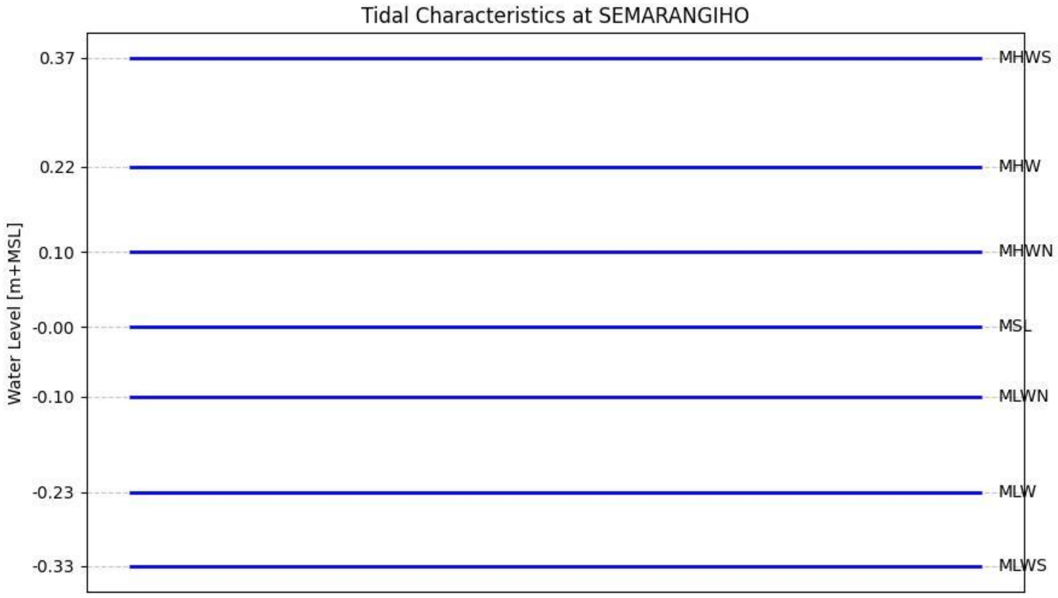


Figure 1:: Tidal spectrum based on IHO data Semarang between 4-10-2024 and 4-10-2025

The tidal amplitude was analysed using a Python script, in which the high astronomical tide, high spring tide, mean high tide, high neap tide, low neap tide, mean low tide, and low spring tide are determined. The model output is shown in Figure 2.



Figuur 2: Tidal range based on IHO data Semarang between 4-10-2024 and 4-10-2025. Relative to MSL.

Wave rose

To determine the significant wave height that could be used as model input, a wave rose approximation is used. This approximation is gathered from an open-access tool, namely Climate Data Store. From this open-access tool, ERA 5 data is manually downloaded. The data represents wave heights, wave directions, and wave periods from January 2014 till January 2024. The wave rose shows the dominant direction in which waves are approaching, the wave height distribution, and the occurrence frequency of the significant wave height expressed in a percentage. Next to a wave rose, also a scatter is gathered. Here, the counts of a certain significant wave height and a wave period are visualized. The wave rose, and the scatter is shown in Figure 3.

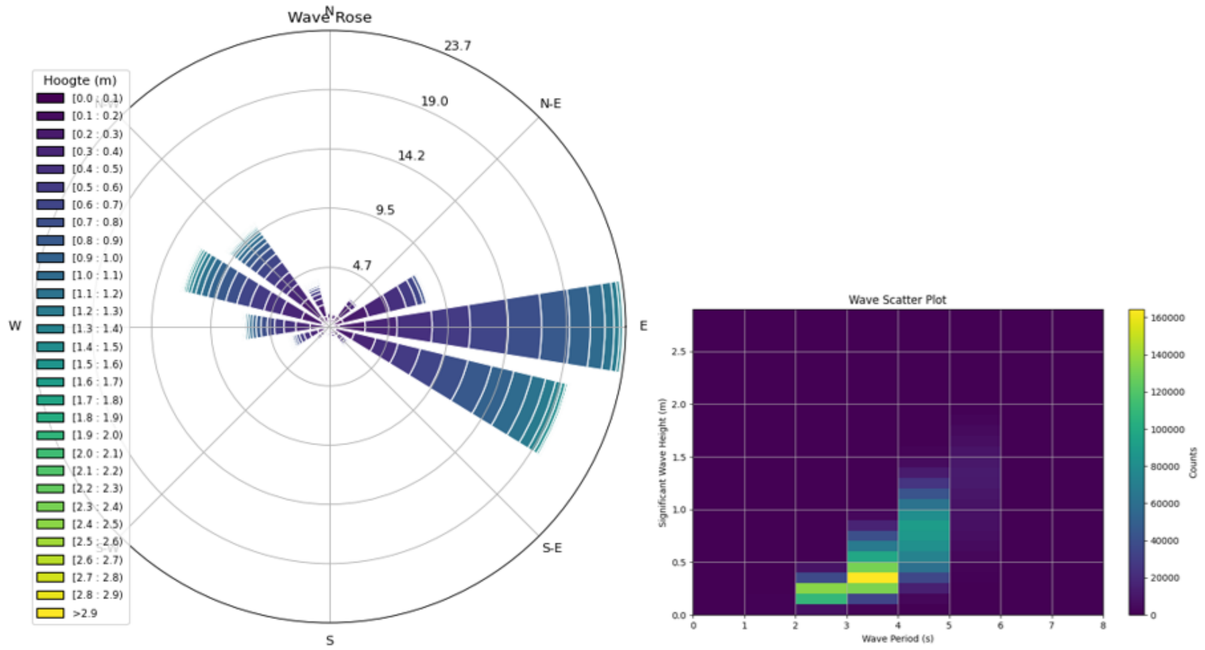


Figure 3:: Wave rose computed from ERA 5 data January 2014 till January 2024

The results from the wave rose, wave scatter, are analysed by the use of a wave scatter table. The scatter table shows the occurrence of wave height bins corresponding to wave period bins. It could be observed that the significant wave height ranges from 0.00m till 2.30m. Accordingly to the wave rose, the most common wave height ranges between 0.10m and 0.60m. According to the wave scatter, the most common wave height was between 0.30m and 0.40m with a wave period of 3 till 4 seconds. Per wave height bin and wave period bin the total percentage of occurrence is calculated. Also the cumulative sum is calculated to determine what wave heights and wave periods are corresponding to occurrence boundaries. The wave heights bin corresponding to an occurrence boundary of 95% represents the upper boundary of the significant wave height that is lower than 95% of all measured waves. This corresponds to a significant wave height of 1.2 meter and a wave period of 5 seconds. The 50% boundary shows the upper boundary for waves that are lower than 50% of the measured waves. This corresponds to a wave height of 0.50 meter (49.6%) and a wave period of 4 seconds (55.8%). The lowest wave height (8.9%) and wave period (17%) correspond to a wave height of 0.20 meter with a wave period of 3 seconds.

Table 1: Overview of wave height bins and different wave period bins

wave_height_bin	(1, 2]	(2, 3]	(3, 4]	(4, 5]	(5, 6]	(6, 7]	(7, 8]	Total	Cumulative sum
(0.0, 0.1]	0,06	0,39	0,08	0	0	0	0	**0,53**	**0,5**
(0.1, 0.2]	0,07	6,2	1,9	0,15	0	0	0	**8,32**	**8,9**
(0.2, 0.3]	0	7,65	7,47	0,83	0,01	0	0	**15,96**	**24,8**
(0.3, 0.4]	0	2,08	9,3	1,96	0,05	0	0	**13,39**	**38,2**
(0.4, 0.5]	0	0,47	7,4	3,39	0,09	0	0	**11,35**	**49,6**
(0.5, 0.6]	0	0,03	5,53	4,13	0,18	0	0	**9,87**	**59,4**
(0.6, 0.7]	0	0	3,81	4,62	0,28	0	0	**8,71**	**68,1**
(0.7, 0.8]	0	0	2,23	4,95	0,36	0	0	**7,54**	**75,7**
(0.8, 0.9]	0	0	0,91	5,12	0,39	0	0	**6,42**	**82,1**
(0.9, 1.0]	0	0	0,19	4,58	0,41	0	0	**5,18**	**87,3**
(1.0, 1.1]	0	0	0,02	3,55	0,45	0	0	**4,02**	**91,3**
(1.1, 1.2]	0	0	0	2,42	0,54	0	0	**2,96**	**94,3**
(1.2, 1.3]	0	0	0	1,44	0,65	0	0	**2,09**	**96,3**
(1.3, 1.4]	0	0	0	0,67	0,67	0	0	**1,34**	**97,7**
(1.4, 1.5]	0	0	0	0,26	0,62	0	0	**0,88**	**98,6**
(1.5, 1.6]	0	0	0	0,08	0,48	0	0	**0,56**	**99,1**
(1.6, 1.7]	0	0	0	0,02	0,36	0	0	**0,38**	**99,5**
(1.7, 1.8]	0	0	0	0	0,22	0	0	**0,22**	**99,7**
(1.8, 1.9]	0	0	0	0	0,12	0	0	**0,12**	**99,8**
(1.9, 2.0]	0	0	0	0	0,07	0,01	0	**0,08**	**99,9**
(2.0, 2.1]	0	0	0	0	0,03	0	0	**0,03**	**100,0**
(2.1, 2.2]	0	0	0	0	0,01	0	0	**0,01**	**100,0**
(2.2, 2.3]	0	0	0	0	0,01	0	0	**0,01**	**100,0**
(2.3, 2.4]	0	0	0	0	0	0	0	**0**	**100,0**
(2.4, 2.5]	0	0	0	0	0	0	0	**0**	**100,0**
(2.5, 2.6]	0	0	0	0	0	0	0	**0**	**100,0**
(2.6, 2.7]	0	0	0	0	0	0	0	**0**	**100,0**
(2.7, 2.8]	0	0	0	0	0	0	0	**0**	**100,0**
(2.8, 2.9]	0	0	0	0	0	0	0	**0**	**100,0**
TOTAL	**0,13**	**16,82**	**38,84**	**38,17**	**6**	**0,01**	**0**	99,97	
Cumulative sum	**0,1**	**17,0**	**55,8**	**94,0**	**100,0**	**100,0**	**100,0**		

Appendix D : Analysis of applicable conditions; intermediate, shallow or deep water conditions

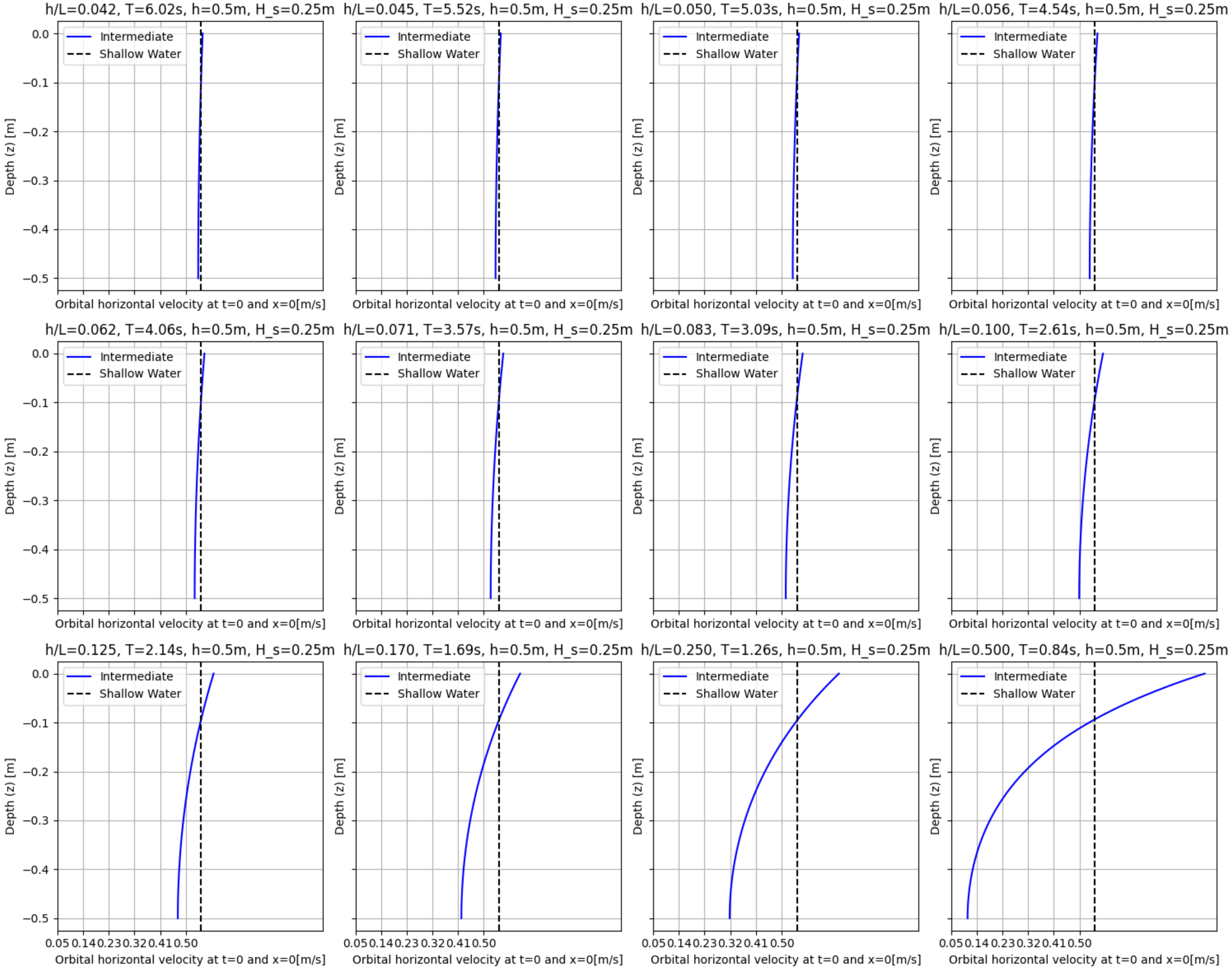


Figure 4: Orbital horizontal velocities for different h/L fractions

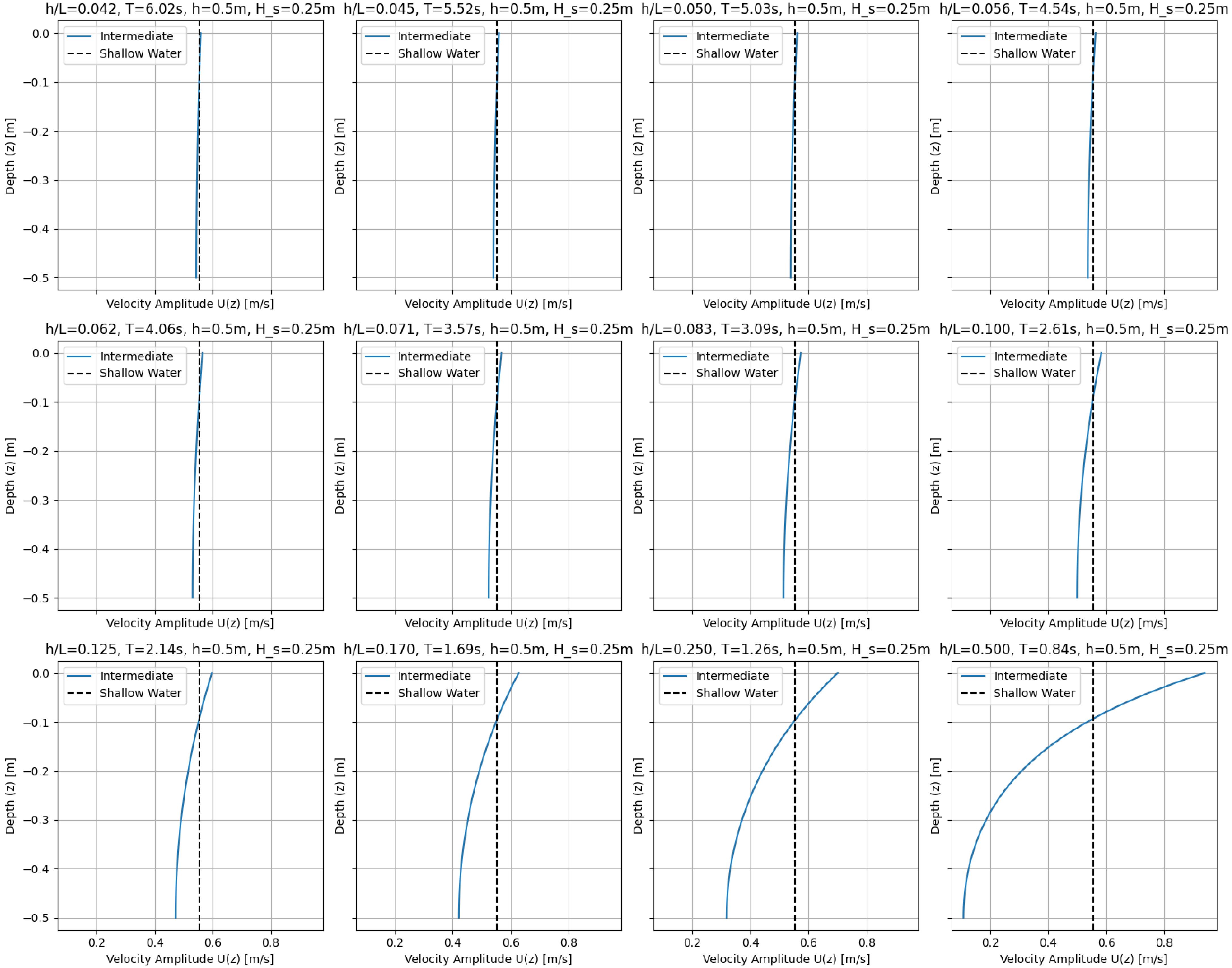


Figure 5: Velocity amplitudes for different h/L fractions

Appendix E: Total wave energy distribution of all possible scenarios

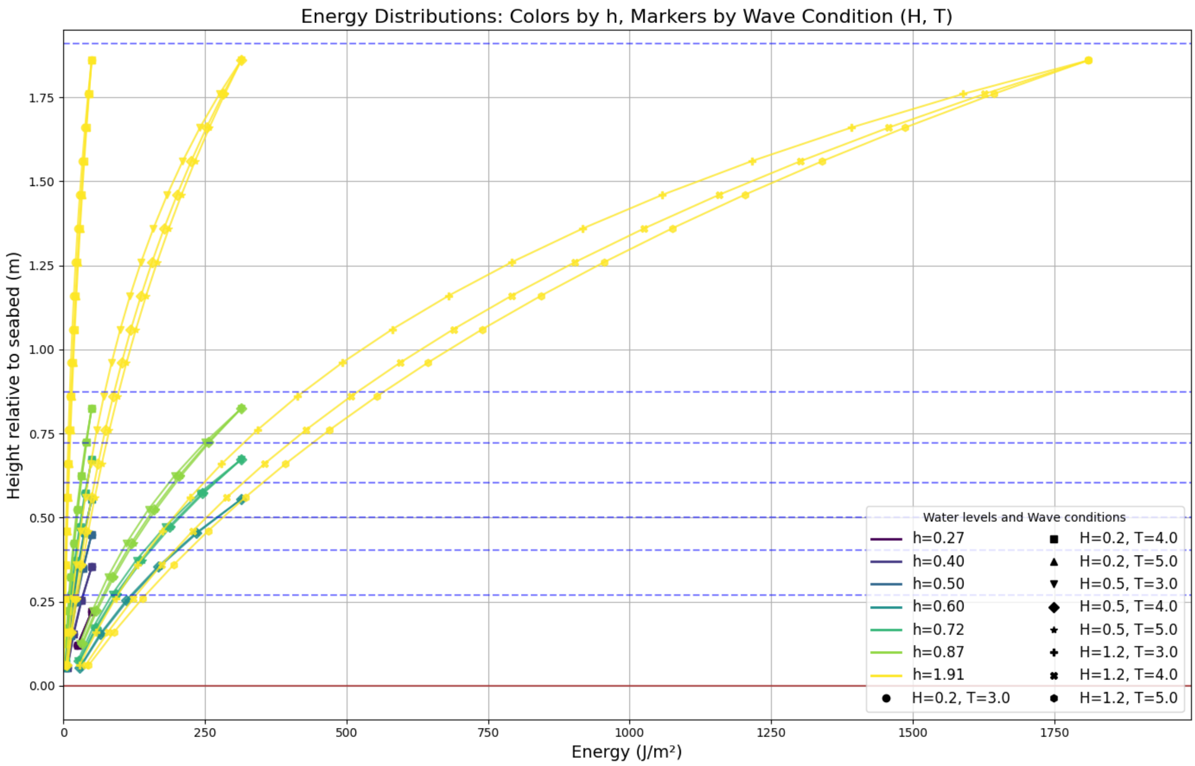


Figure 6: Cumulative total wave energy distribution for all water levels , wave heights, and wave periods

Appendix F: Critical wave energy per age for all water depths

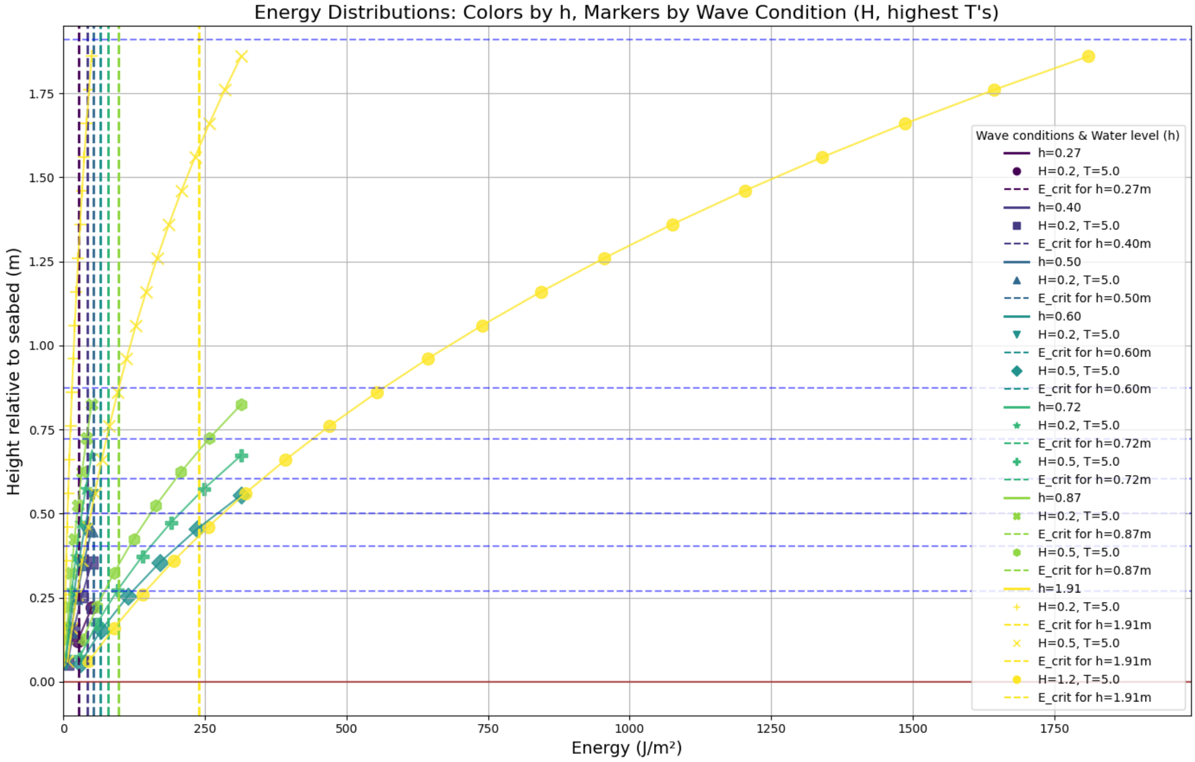


Figure 6: Cumulative total wave energy distribution for all water levels, wave heights, and wave periods together with the critical wave energy for mangrove seedlings of an age of 220 days

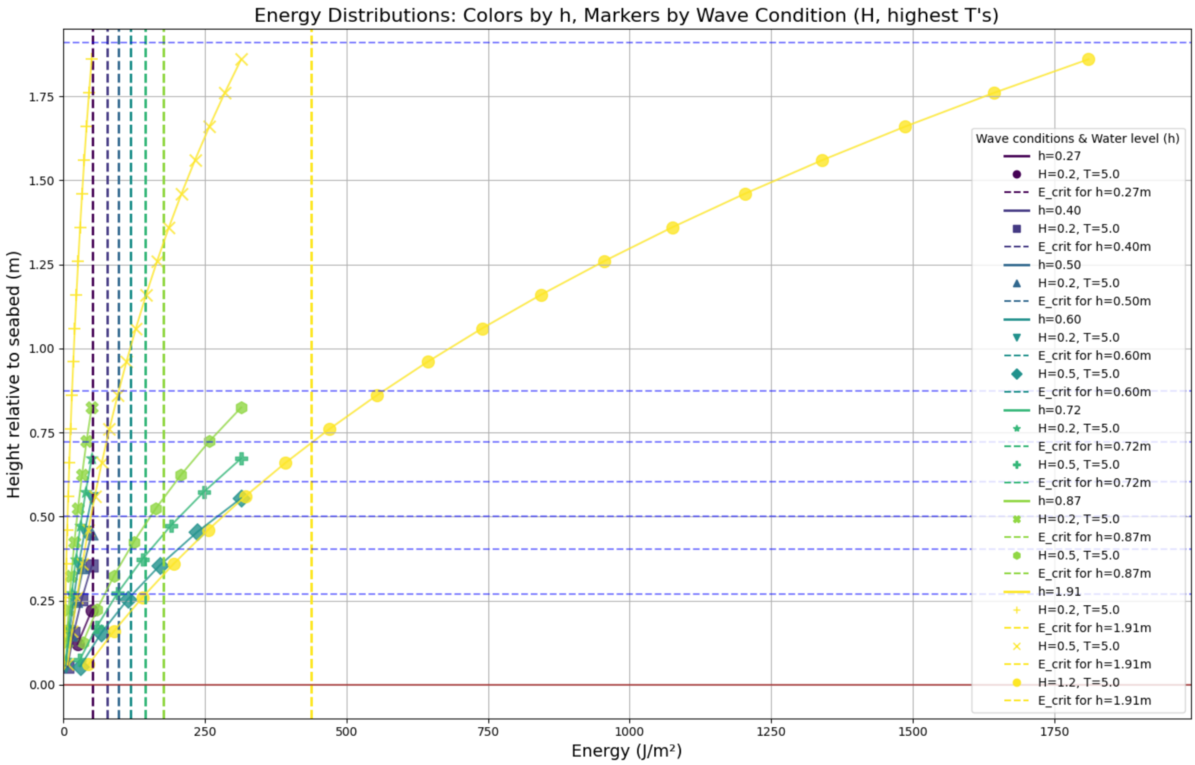


Figure 7: Cumulative total wave energy distribution for all water levels, wave heights, and wave periods together with the critical wave energy for mangrove seedlings of an age of 250 days

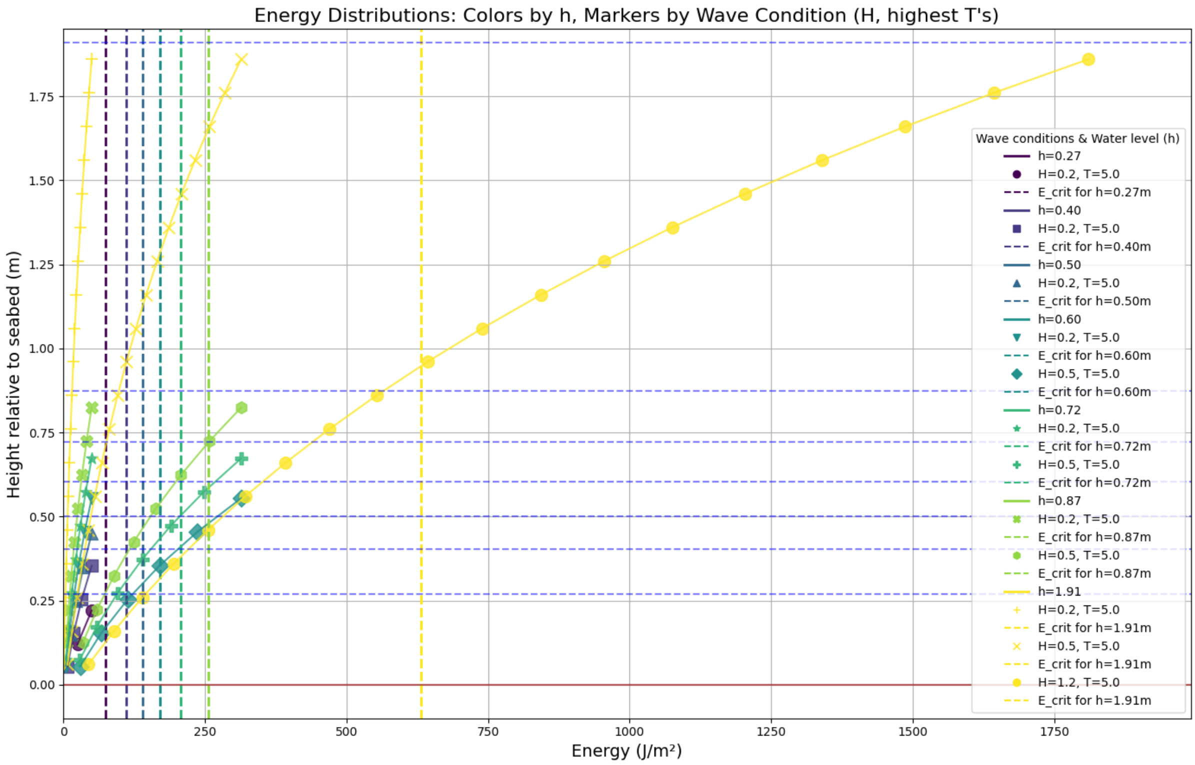


Figure 8: Cumulative total wave energy distribution for all water levels, wave heights, and wave periods together with the critical wave energy for mangrove seedlings of an age of 280 days.

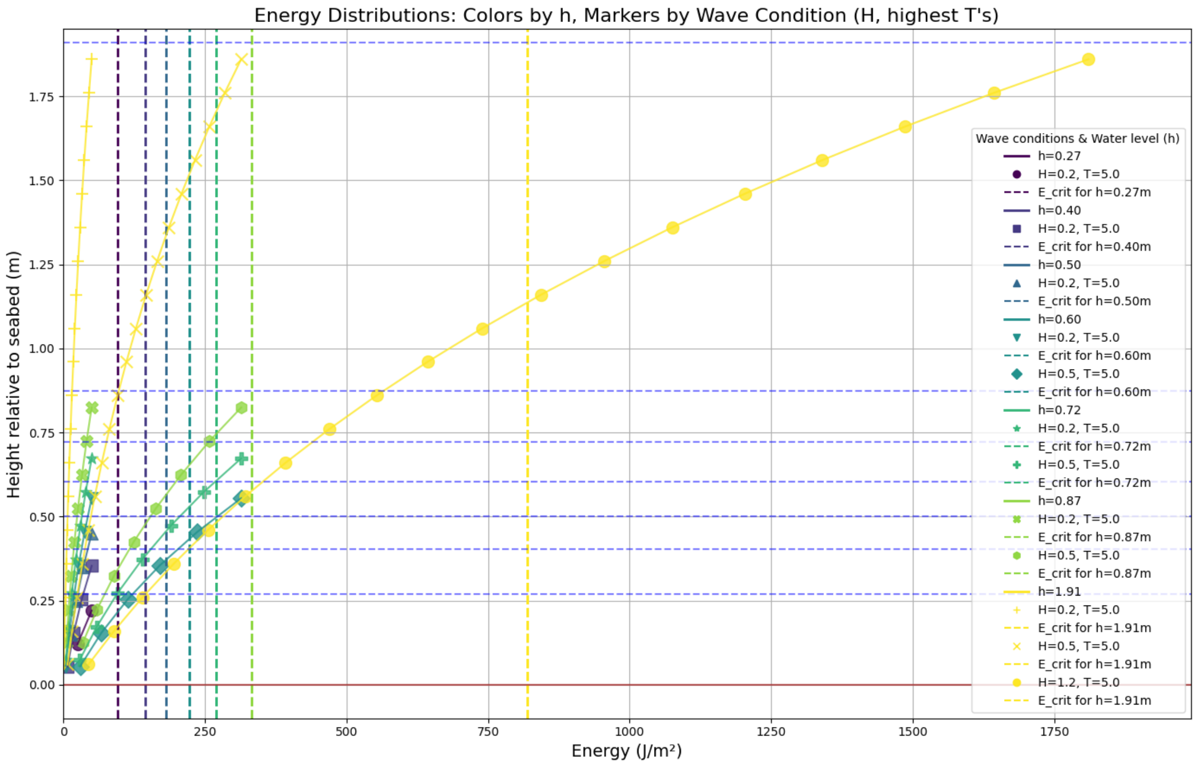


Figure 9: Cumulative total wave energy distribution for all water levels, wave heights, and wave periods together with the critical wave energy for mangrove seedlings of an age of 310 days

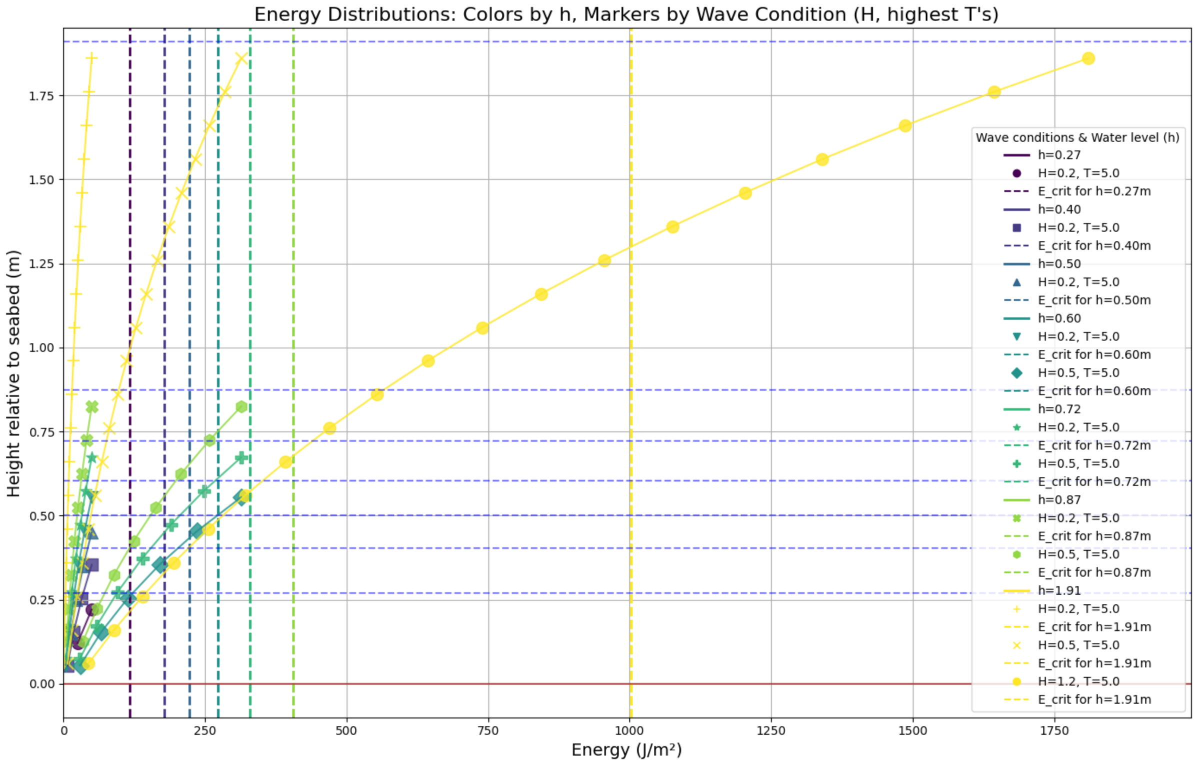


Figure 10: Cumulative total wave energy distribution for all water levels, wave heights, and wave periods together with the critical wave energy for mangrove seedlings of an age of 340 days

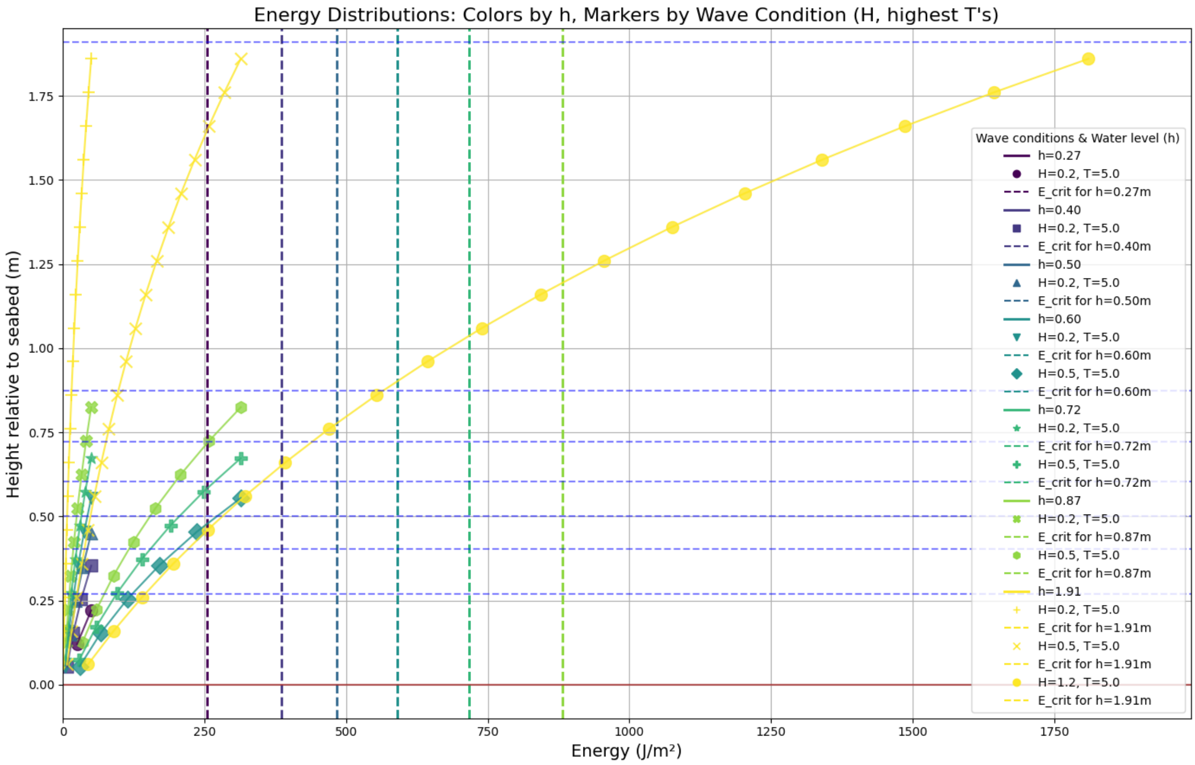


Figure 11: Cumulative total wave energy distribution for all water levels, wave heights, and wave periods together with the critical wave energy for mangrove seedlings of an age of 545 days.

Appendix G: finding the optimum design

Design option 2

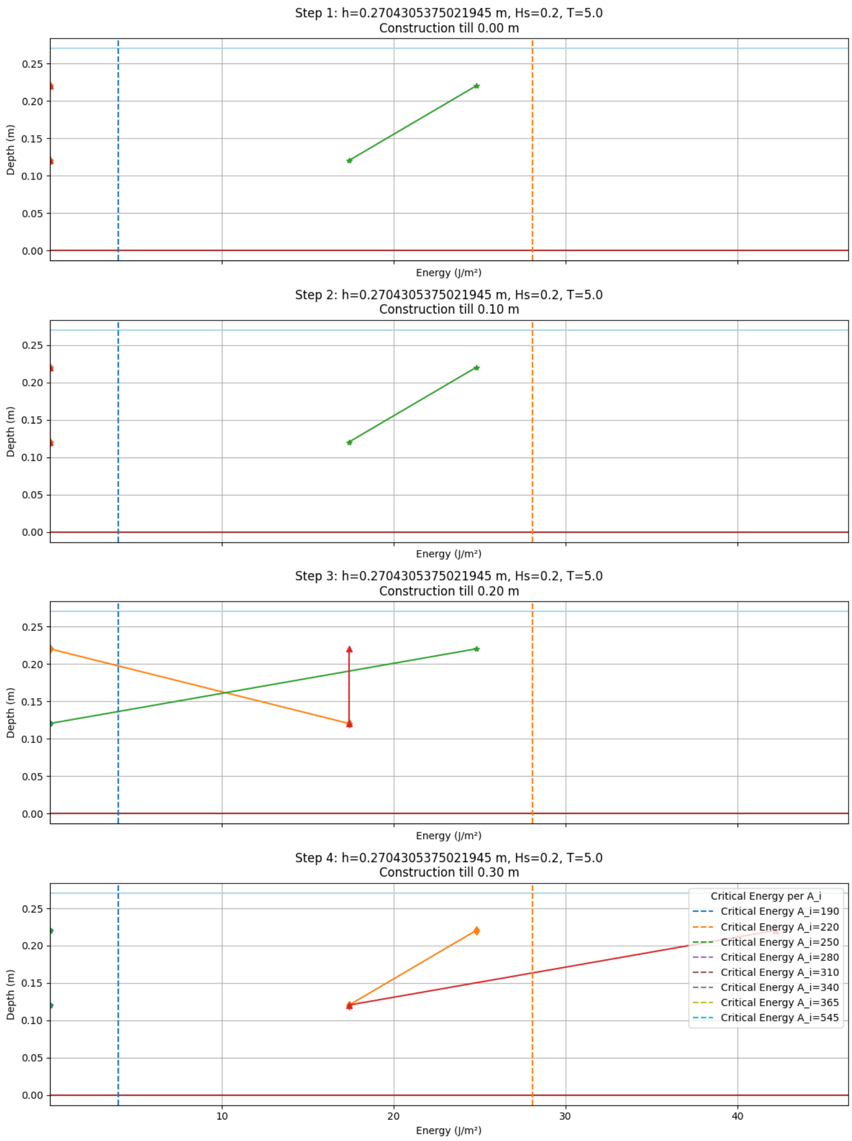


Figure 12: Model output of the simulation of design option 2 under MLT conditions.

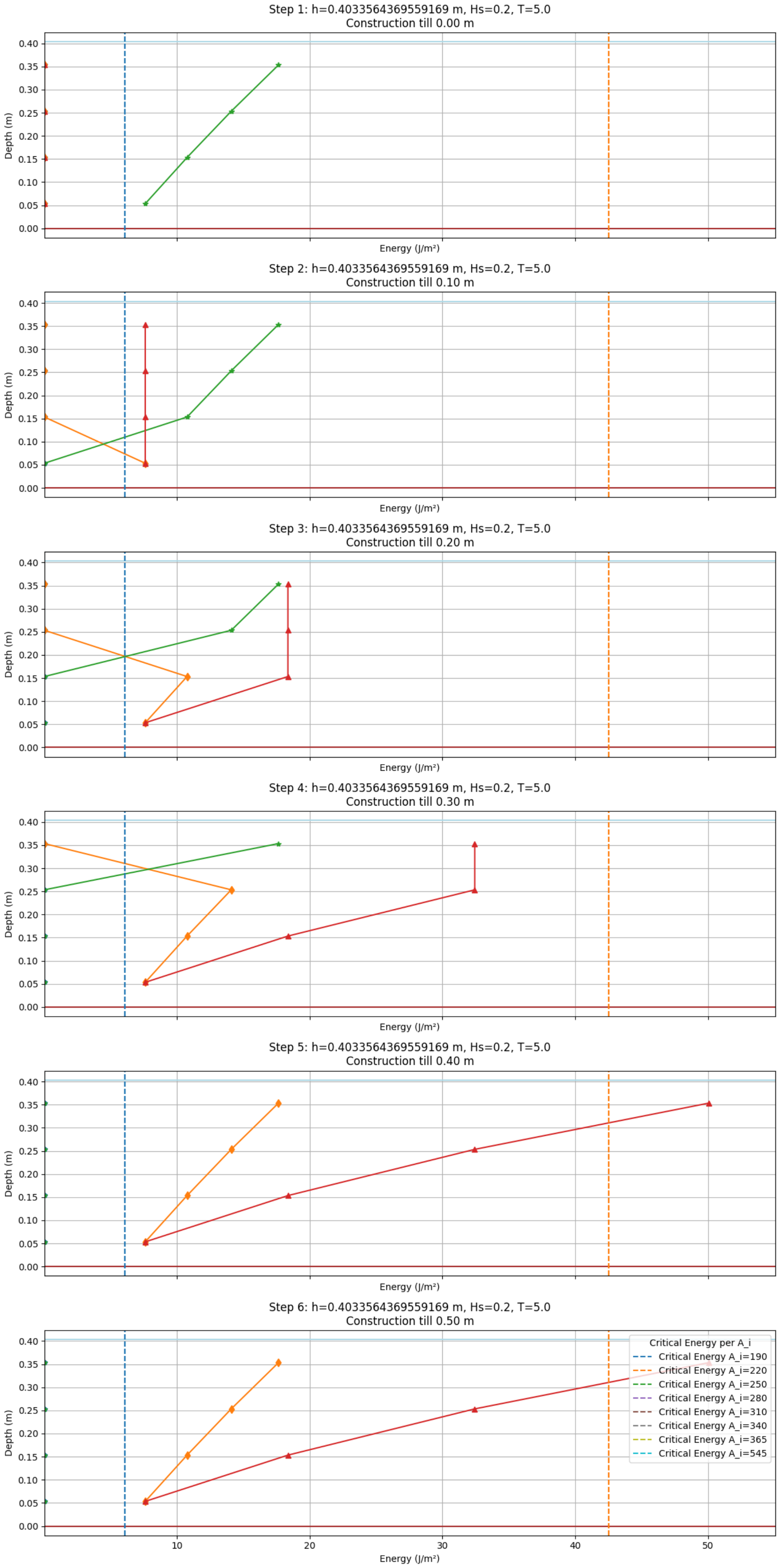


Figure 13: Model output of the simulation of design option 2 under NLT conditions.

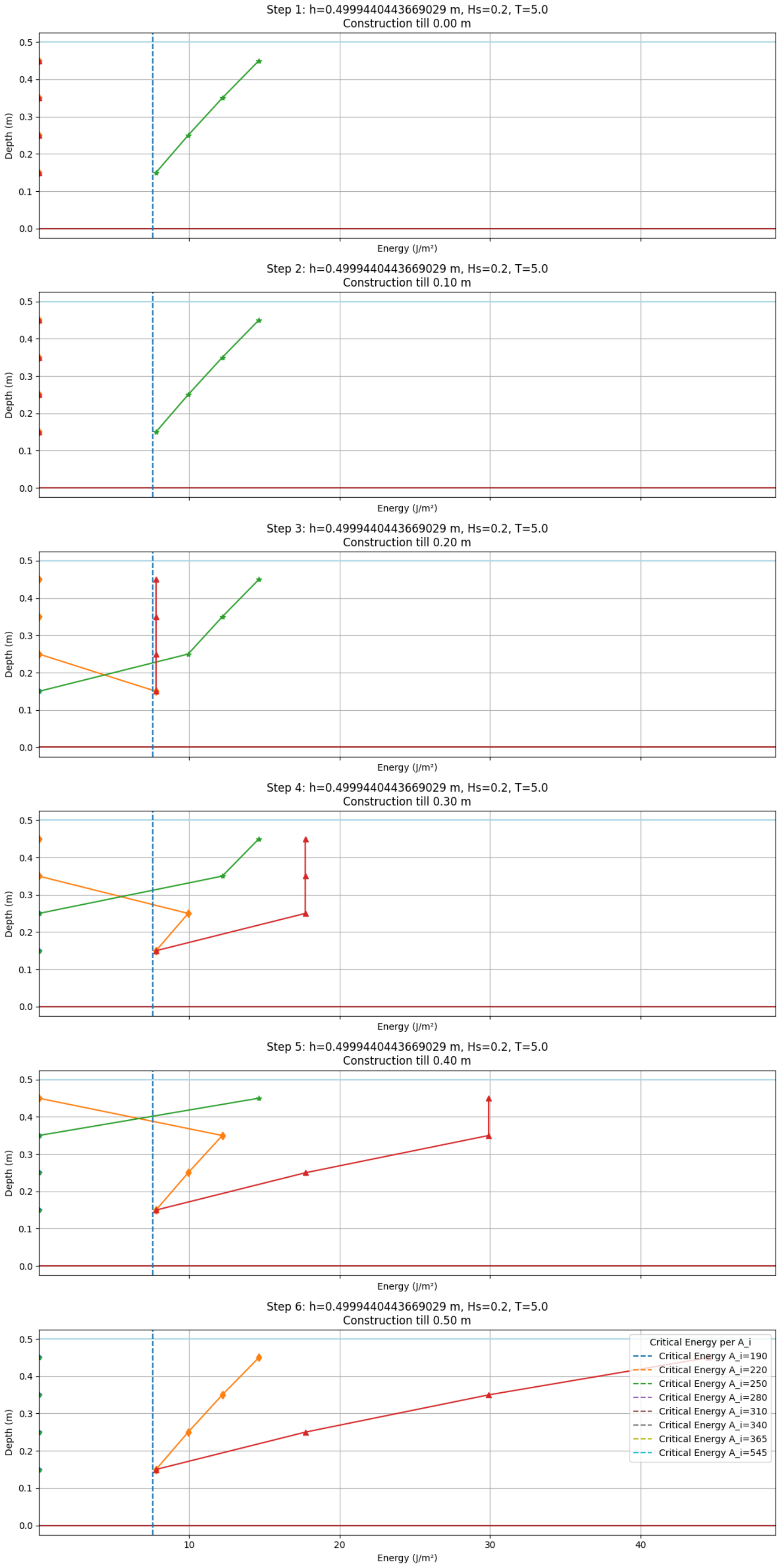


Figure 14: Model output of the simulation of design option 2 under MLT conditions.

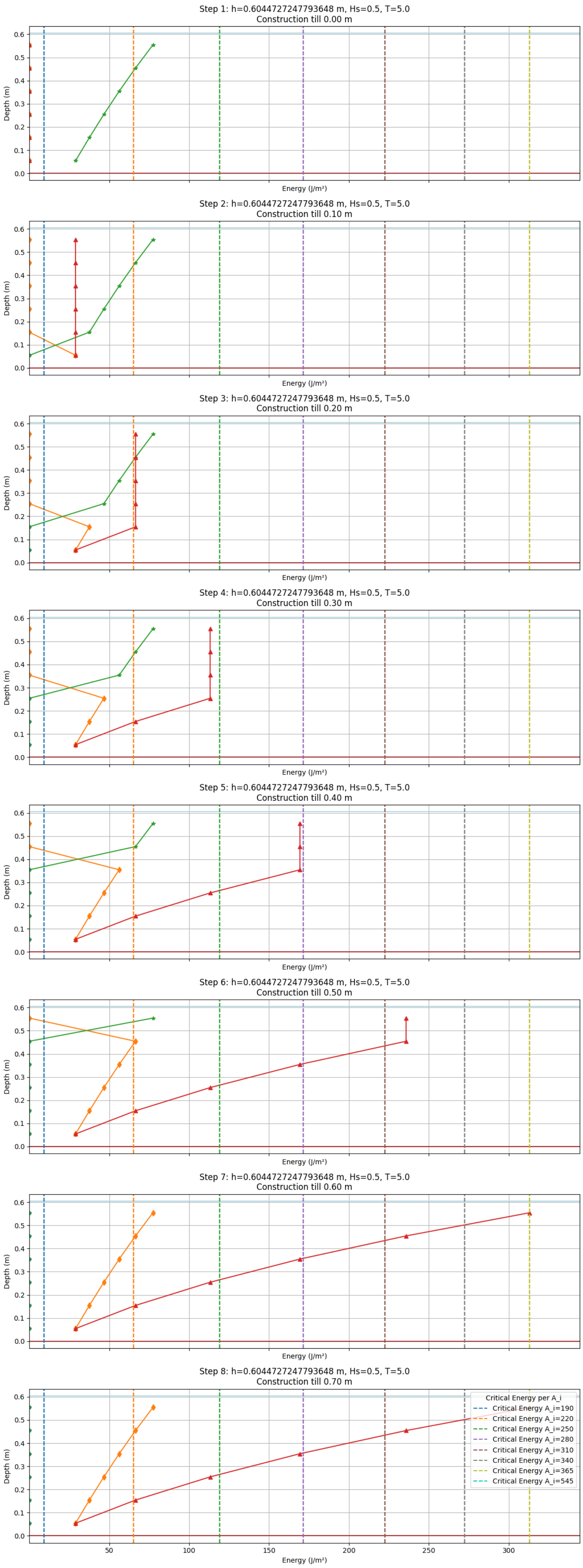


Figure 15: Model output of the simulation of design option 2 under NHT conditions.

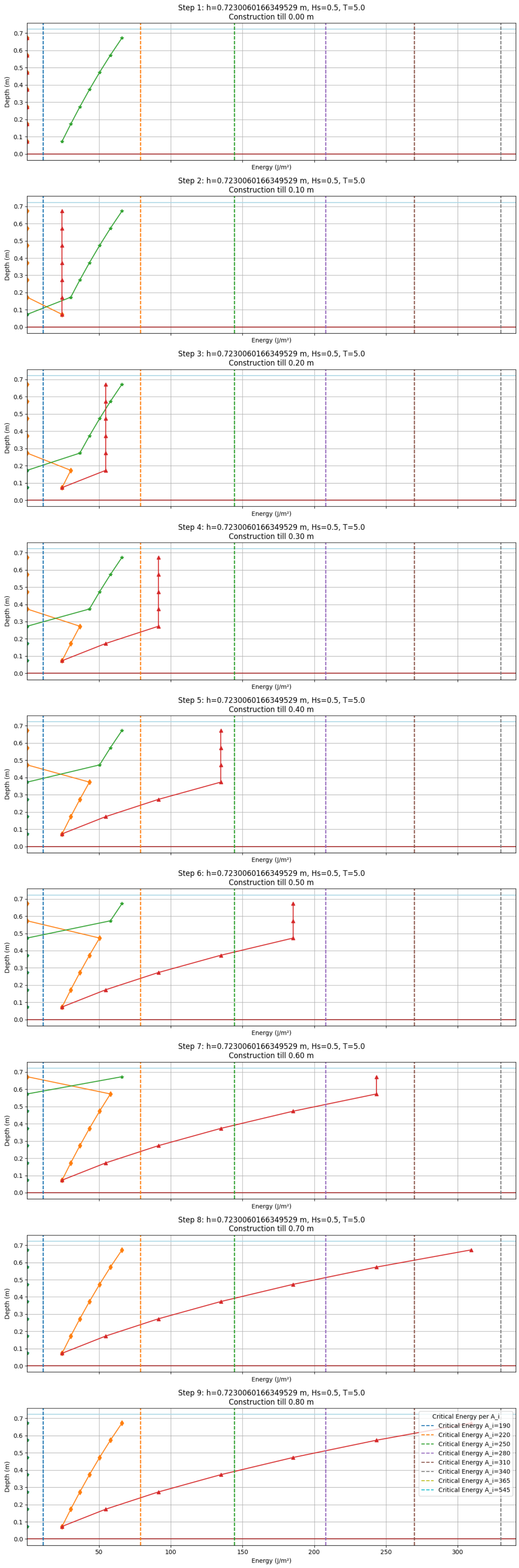


Figure 16: Model output of the simulation of design option 2 under MHT conditions.

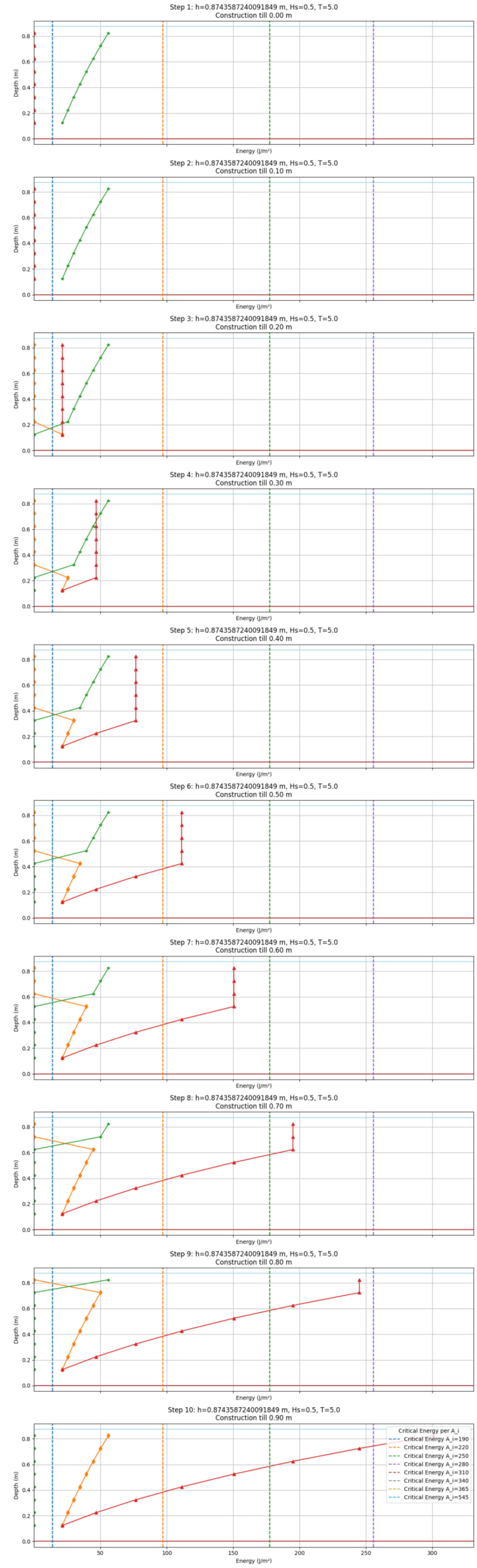


Figure 17: Model output of the simulation of design option 2 under NHT conditions.

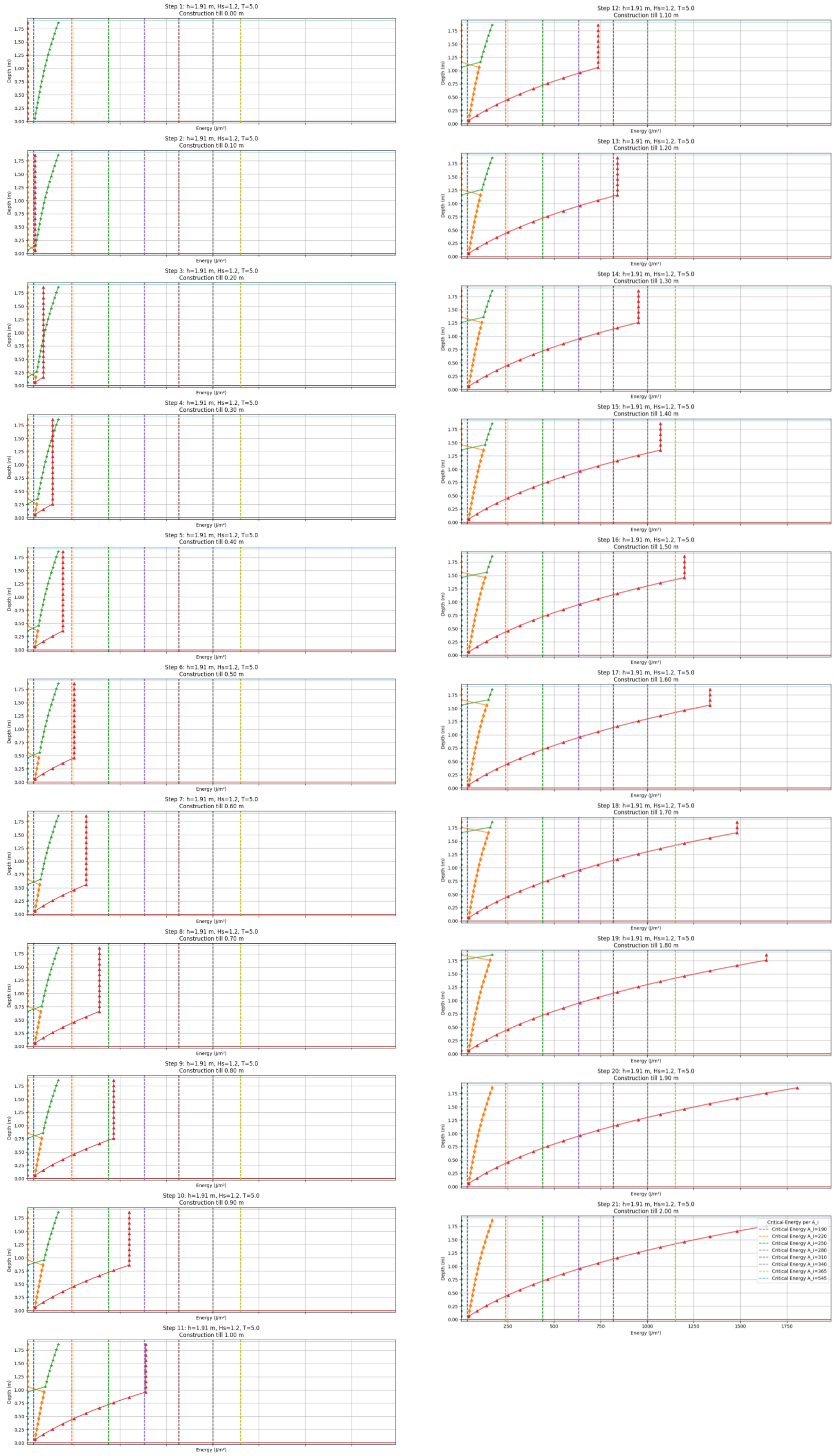


Figure 18: Model output of the simulation of design option 2 under storm condition

Design option 3

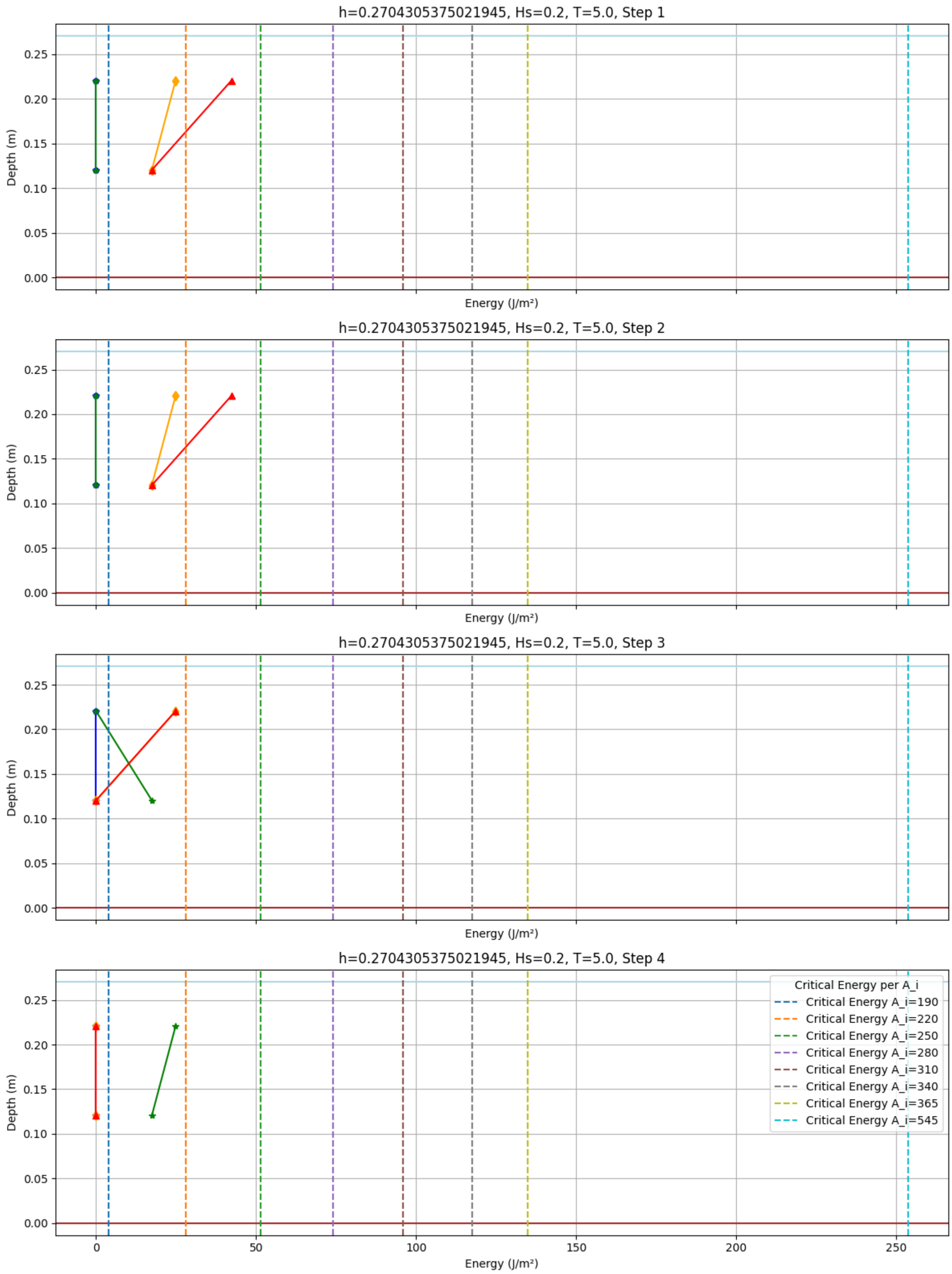


Figure 19: Model output of the simulation of design option 3 under MLT conditions.

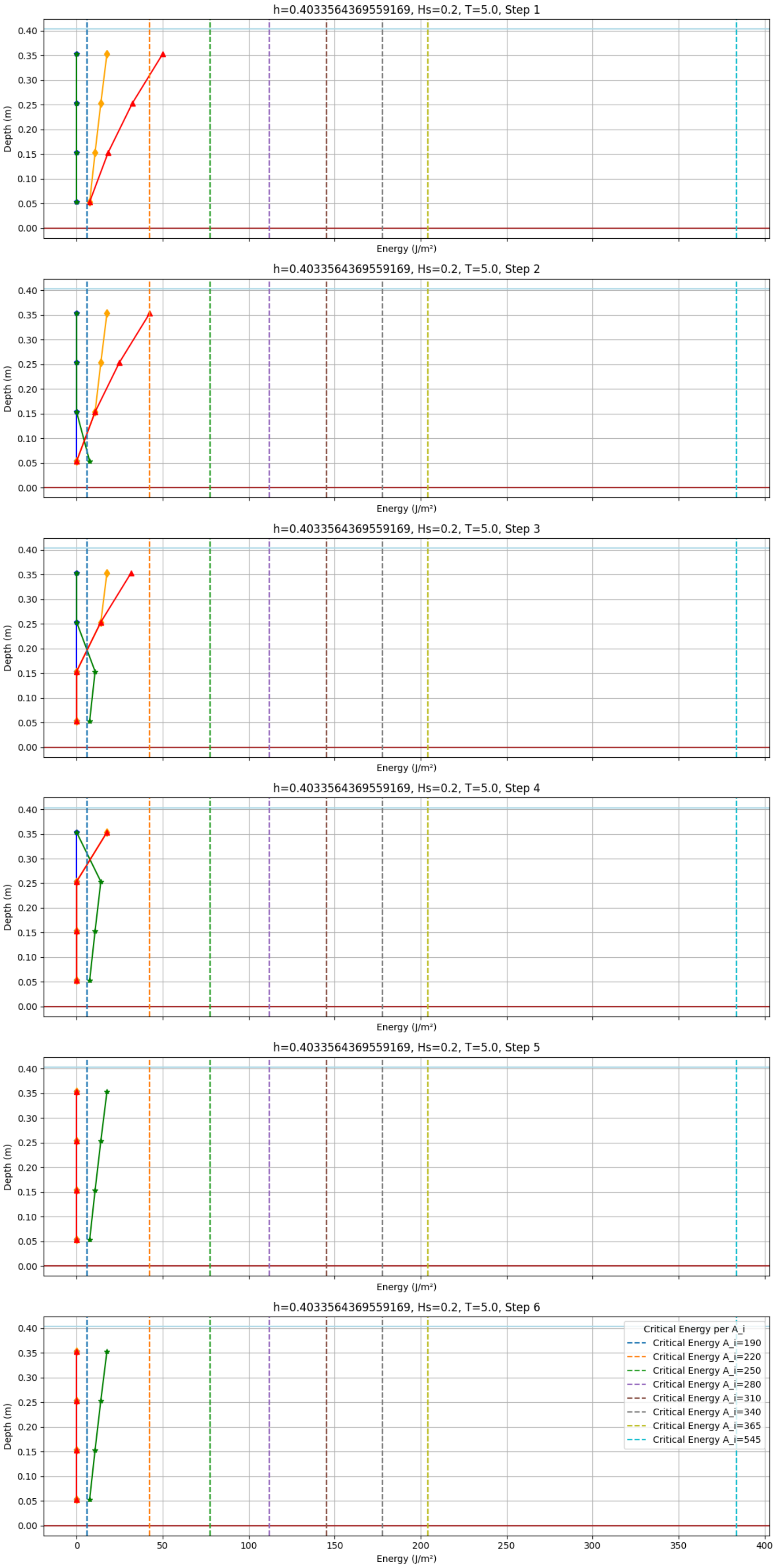


Figure 20: Model output of the simulation of design option 3 under NLT conditions.

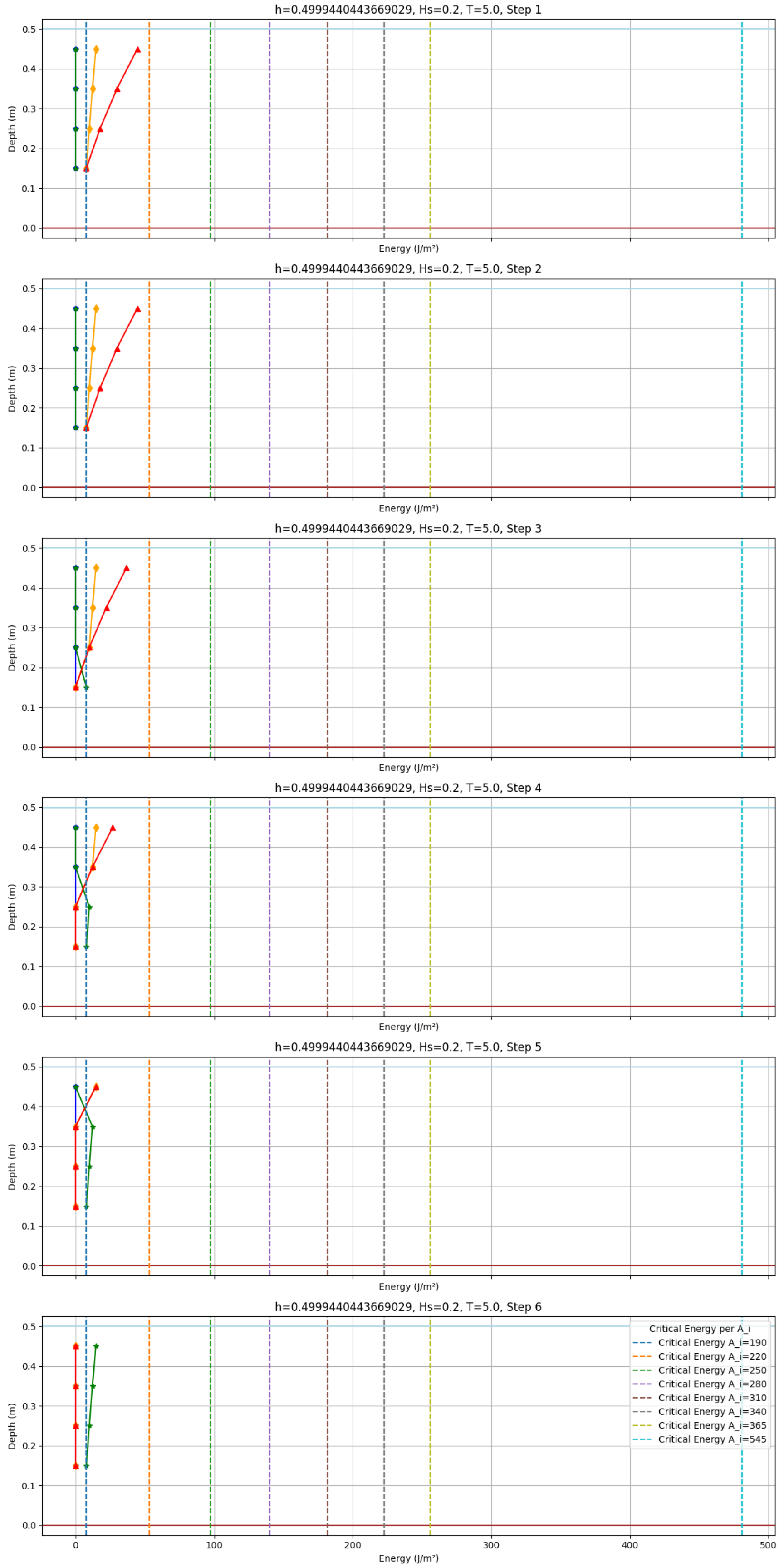


Figure 21: Model output of the simulation of design option 3 under MLT conditions.

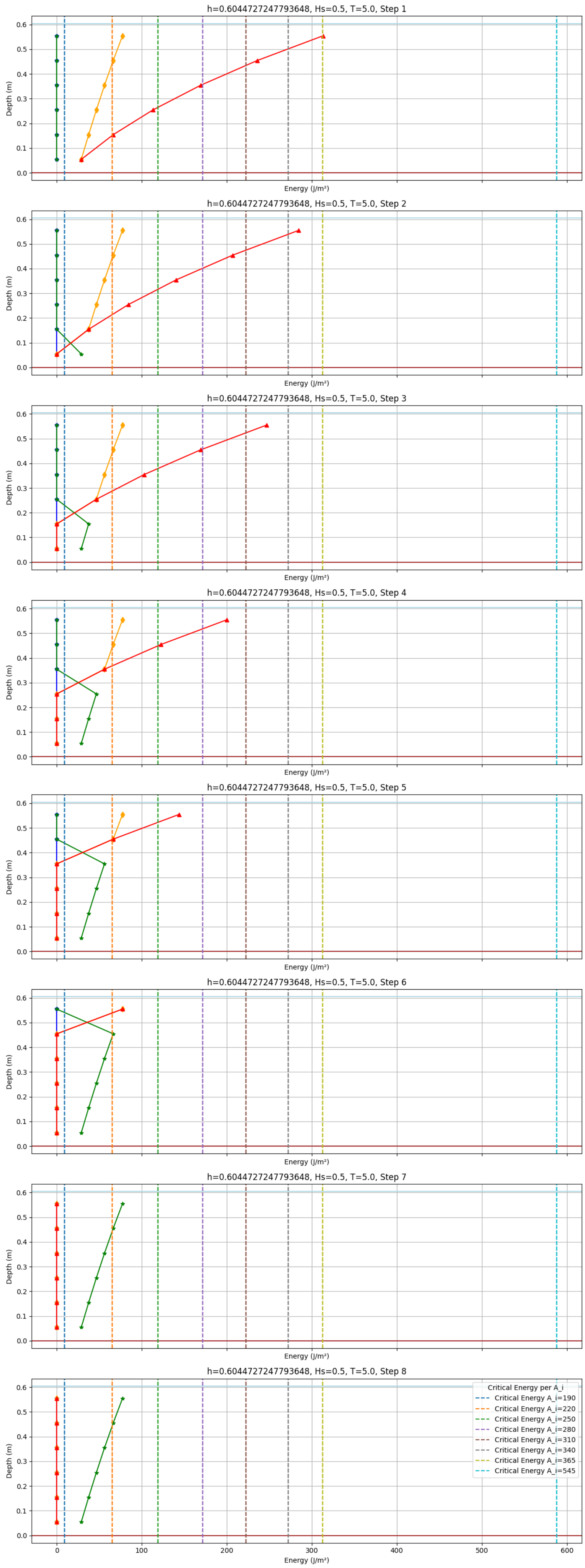


Figure 22: Model output of the simulation of design option 3 under NHT conditions.

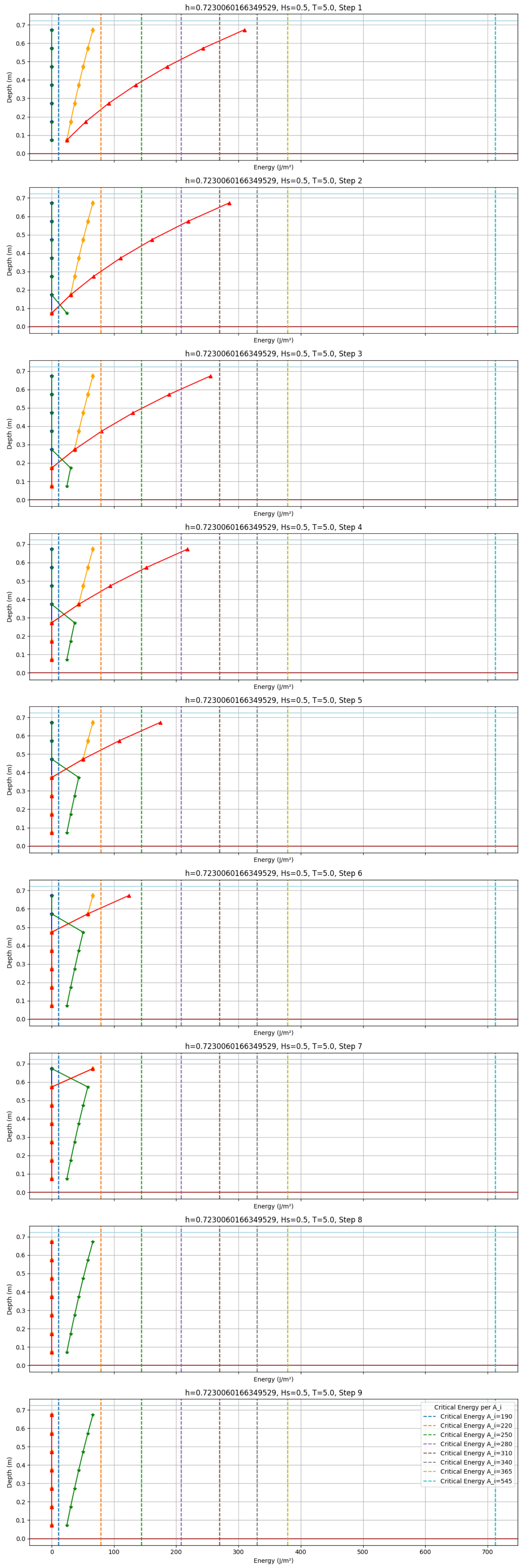


Figure 23: Model output of the simulation of design option 3 under MHT conditions.

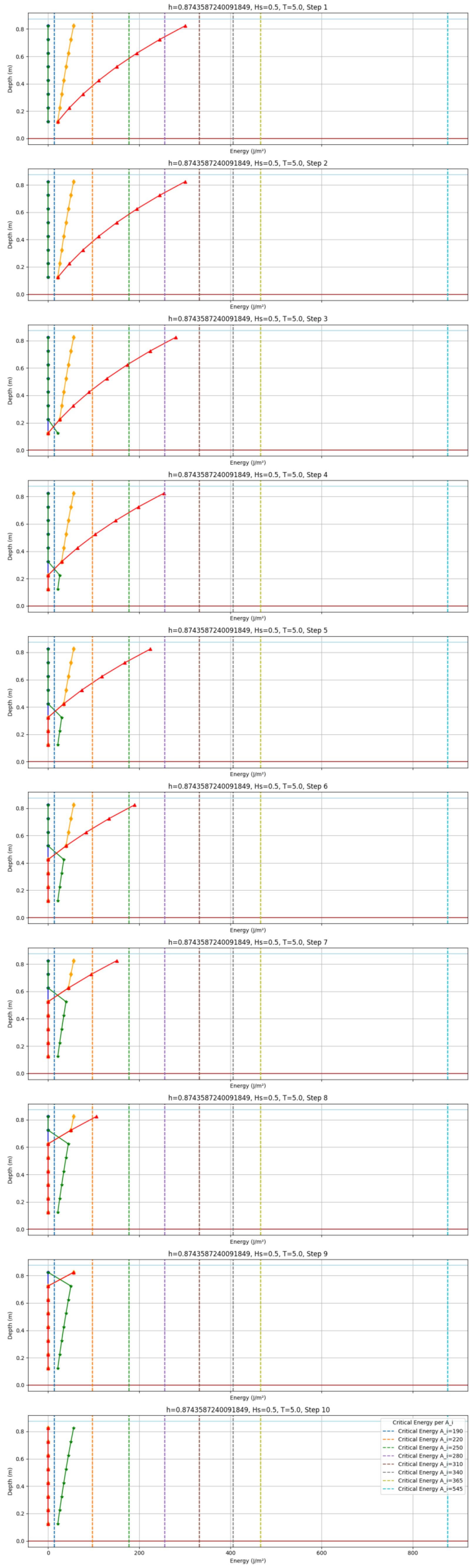


Figure 24: Model output of the simulation of design option 3 under SHT conditions.

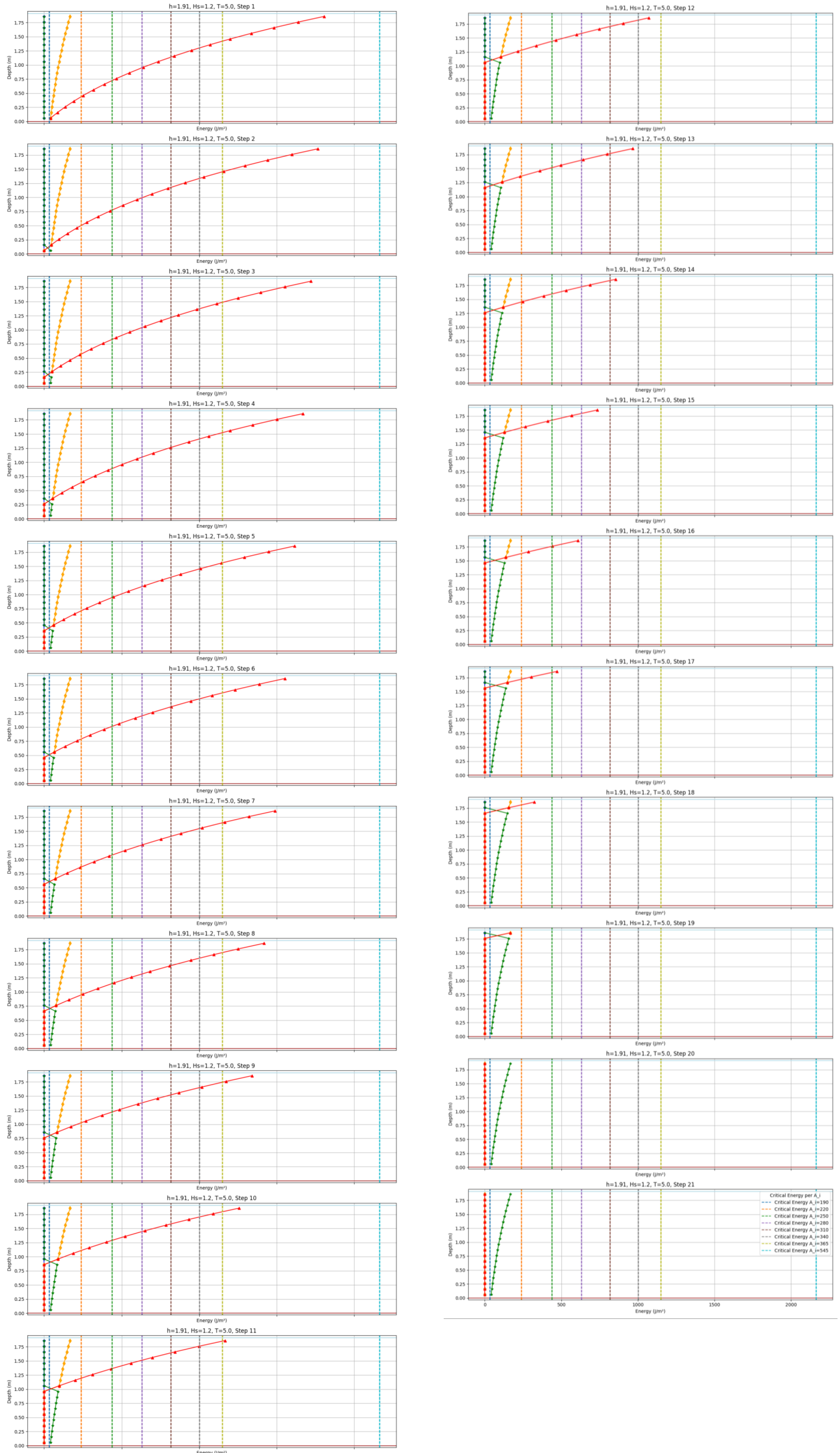


Figure 25: Model output of the simulation of design option 3 under storm conditions

Design option 4

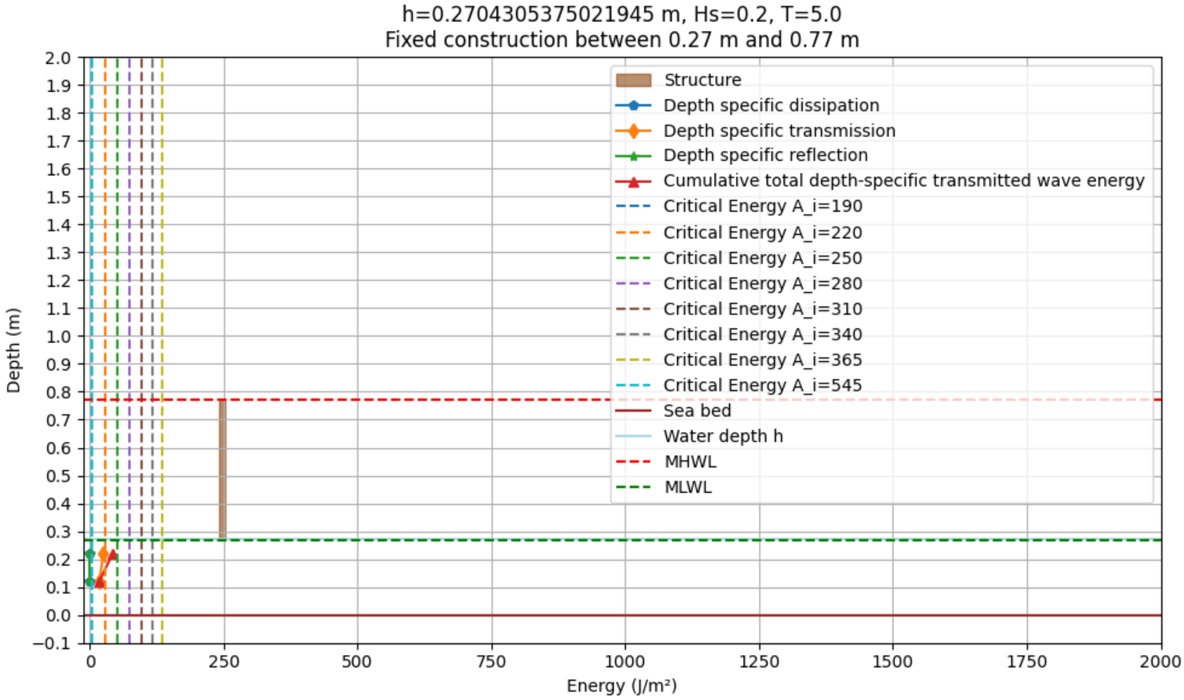


Figure 26: Model output of the simulation of design option 4 under MLT conditions

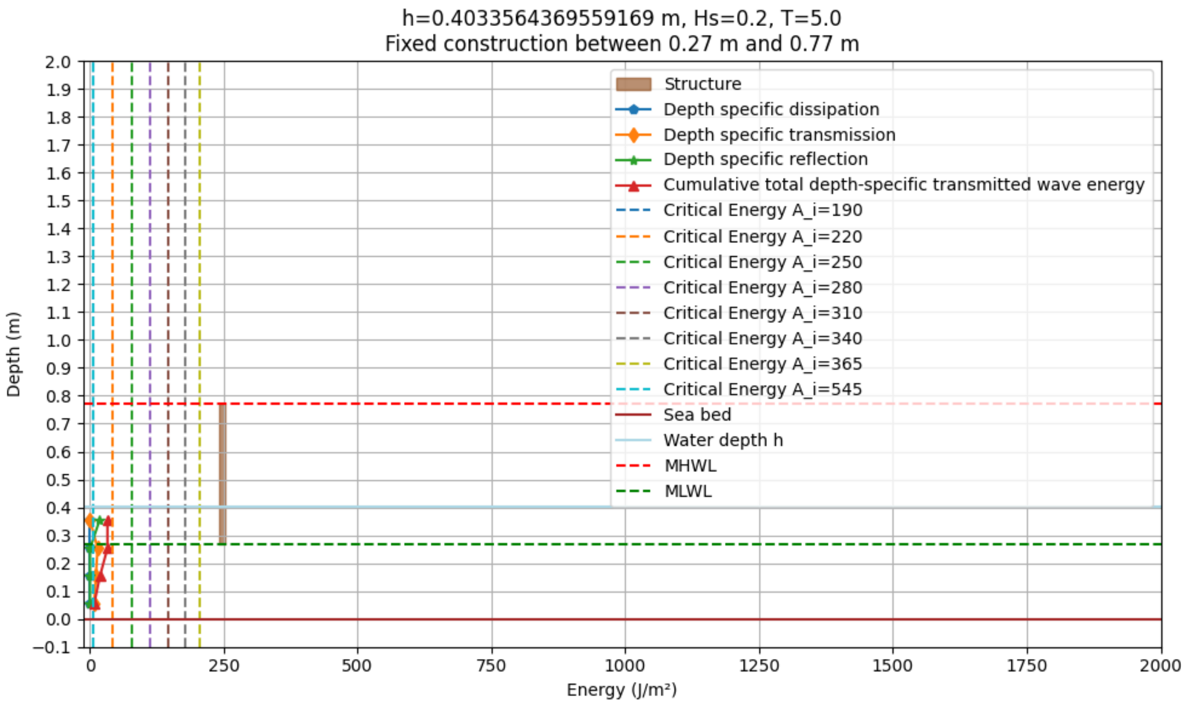


Figure 27: Model output of the simulation of design option 4 under NLT conditions

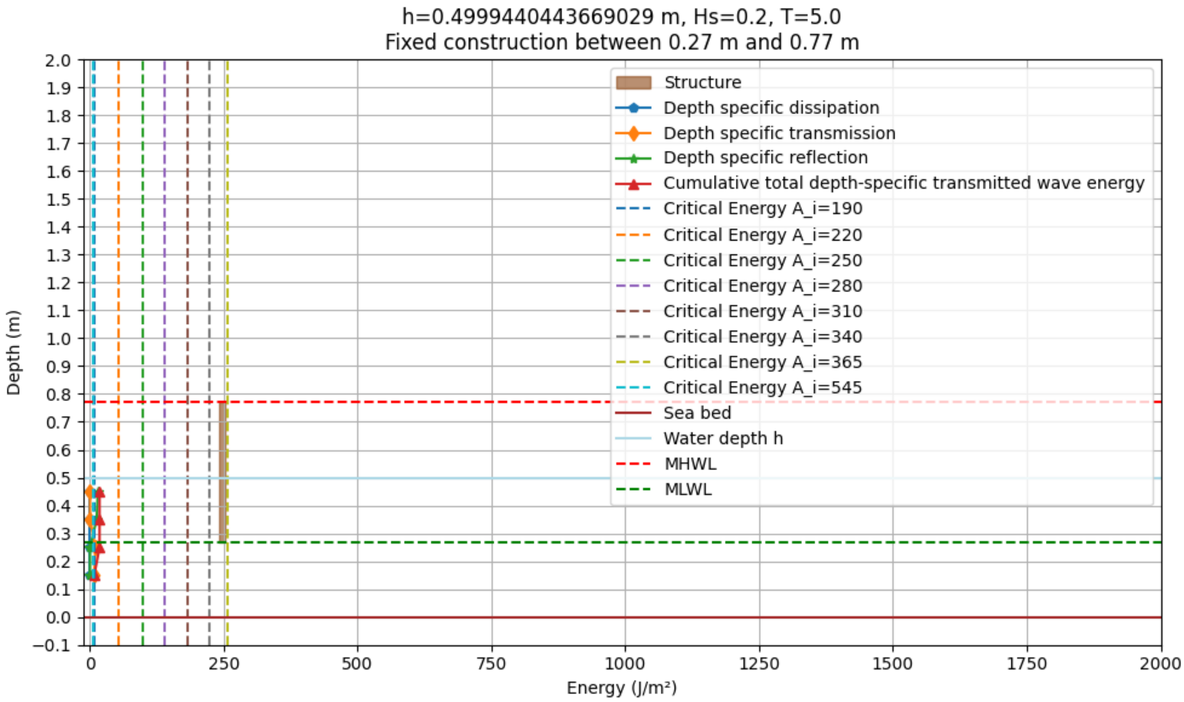


Figure 28: Model output of the simulation of design option 4 under MSL conditions

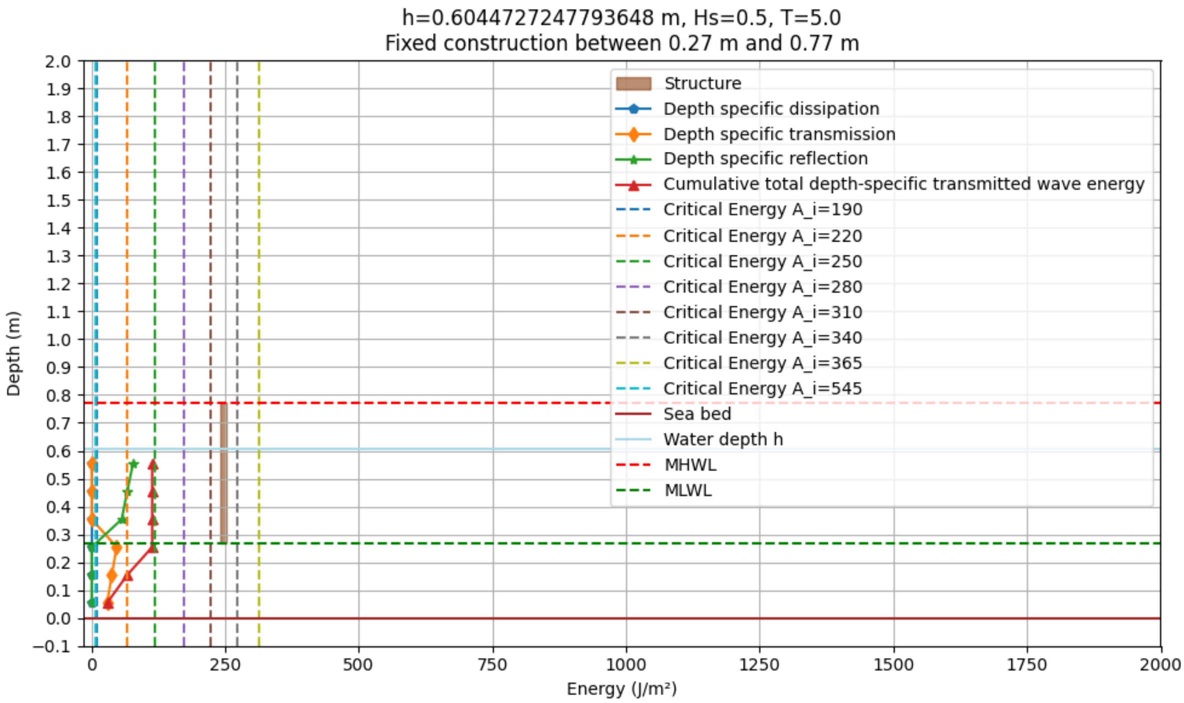


Figure 29: Model output of the simulation of design option 4 under NHT conditions

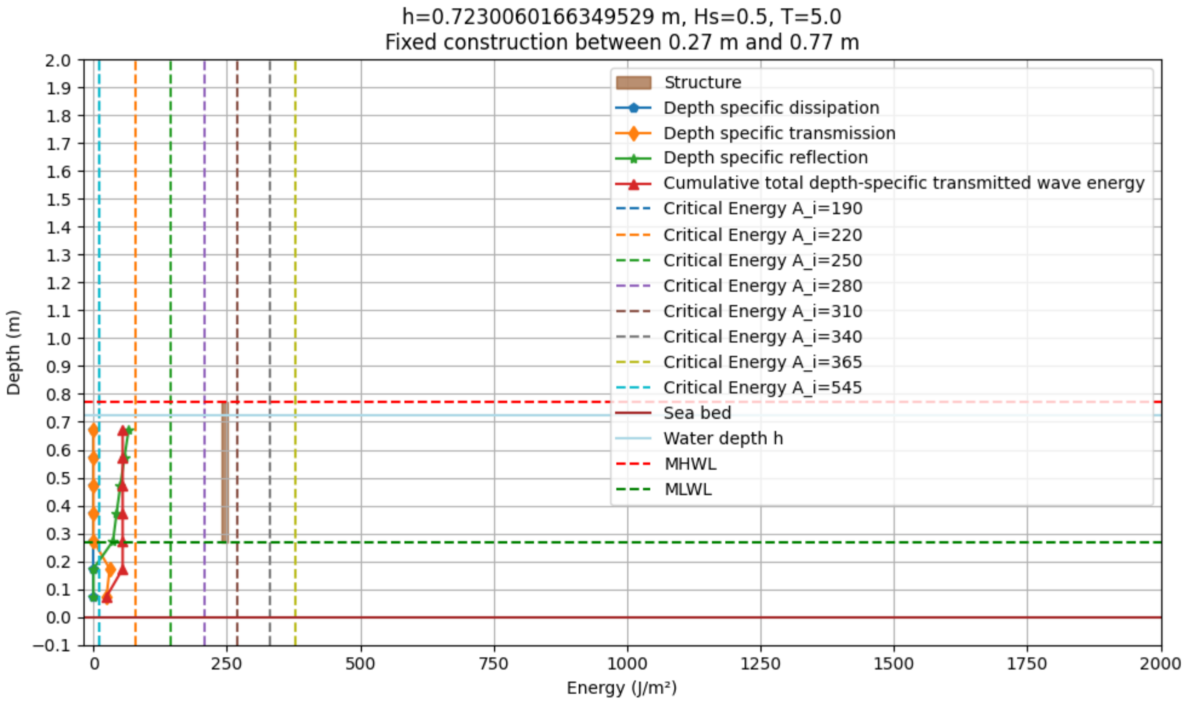


Figure 30: Model output of the simulation of design option 4 under MHT conditions

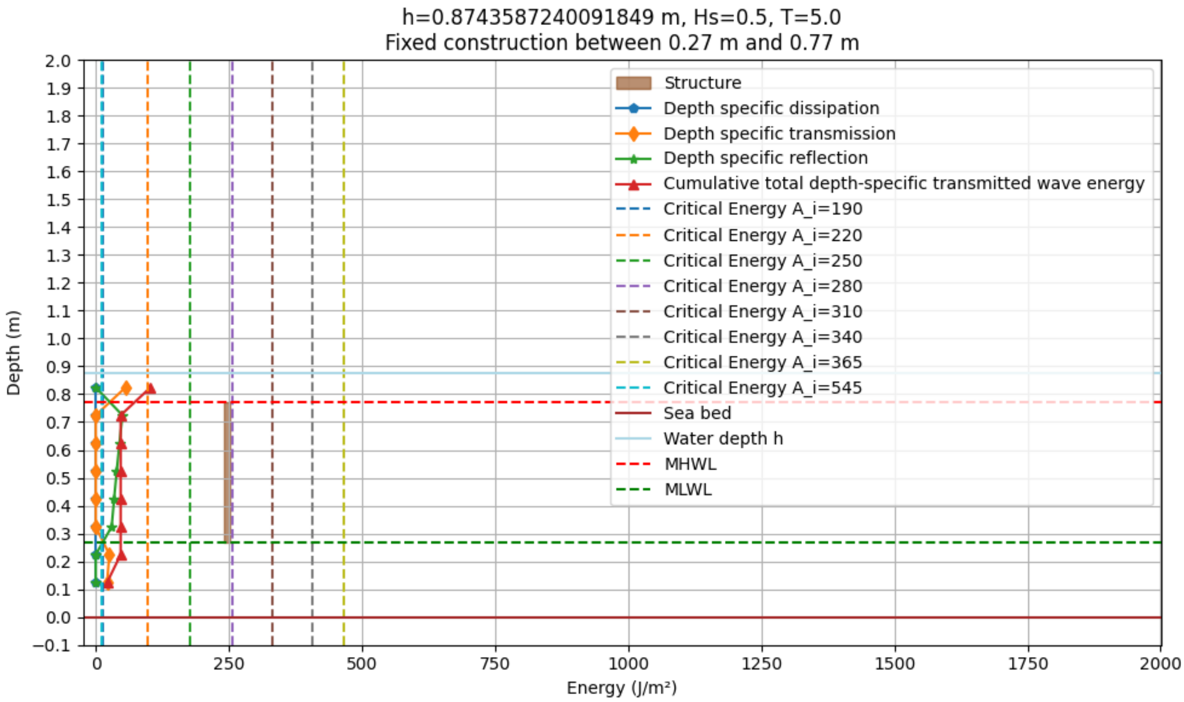


Figure 31: Model output of the simulation of design option 4 under SHT conditions

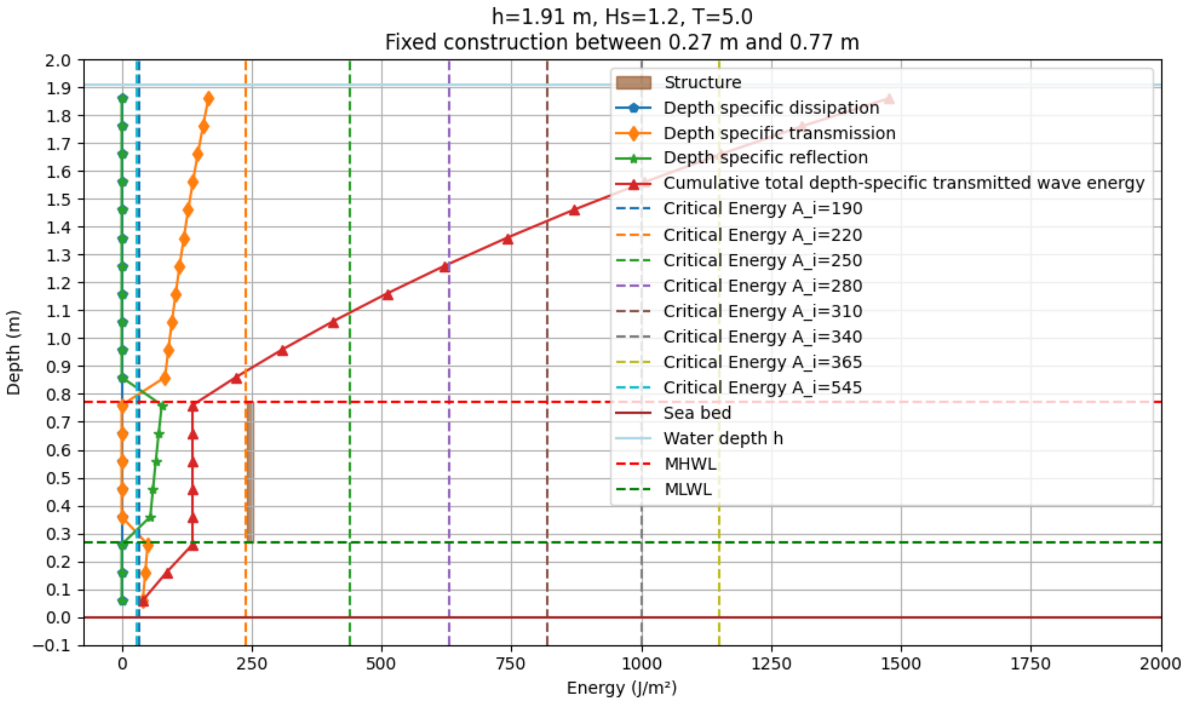


Figure 32: Model output of the simulation of design option 4 under storm conditions

Appendix H Reporting Expert Elicitation

Datum: 08-04-2025
Expert: Joost Noordermeer
Taal: Nederlands

Vragen en Antwoorden

Vraag 1: Wat is uw expertise op het gebied van doorlatende constructies die worden gebruikt voor mangroveherstelprojecten, in het bijzonder met betrekking tot het reguleren van golfenergie en golfhoogte?

Antwoord: Mijn expertise is voornamelijk praktisch en opgedaan tijdens directe betrokkenheid bij projecten zoals het mangroveherstel in Demak, Indonesië. Toen Tom terugkeerde naar Nederland, heb ik de leiding overgenomen. IK heb geëxperimenteerd met verschillende permeabele structuren. Ik kwam hier verschillende uitdagingen tegen, zoals onderhoud, sterkte over tijd, en de effectiviteit in het opvangen en afdragen van golven. Ik hield me bezig met verschillende structuur types, zoals palenrijen vergelijkbaar met hekwerken, van materialen zoals heel en gespleten bamboe, en andere lokaal beschikbare materialen. Lokale gemeenschappen werden bij het ontwerpproces betrokken. Op deze manier konden we gebruikmaken van hun kennis en ervaring. Door de variatie in de natuurlijke omstandigheden en de beperkte duur van metingen is het lastig om in de praktijk de effectiviteit van de structuren te evalueren.

Vraag 2: Waar heeft u deze expertise opgedaan?

Antwoord: Mijn ervaring en expertise zijn opgedaan in Indonesië en Nieuw-Caledonië, waar ik betrokken was bij diverse mangroveherstelprojecten en het implementeren van permeabele structuren.

Vraag 3: Hoe zou u de huidige manier van het ontwerpen van waterdoorlatende constructies en de verschillende ontwerpen die worden gebruikt in mangroveherstelprojecten beschrijven, in het bijzonder met betrekking tot de dissipatie van golfenergie en de reductie van golfhoogte?

Antwoord: Het ontwerp van waterdoorlatende structuren is vaak niet het meeste gericht op de regulering van golfenergie en golfhoogte. De beschikbaarheid van materialen en lokale bouwmethoden is erg belangrijk, vooral omdat deze structuren worden toegepast bij gemeenschappen met een laag opleidingsniveau. Wij draaien het ontwerpproces om door gemeenschappen te vragen hoe zij normaal gesproken materialen gebruiken en vertalen dat naar een ontwerp. Het ontwerp is vaak gebaseerd op gevoel en observatie van de verhouding tussen openheid van de structuur en zijn stabiliteit. Tijdens projecten ontdekken we factoren die het ontwerp beïnvloeden. Een voorbeeld is de aanwezigheid van shipworm in het water. Hierdoor hebben we ook PVC buizen toegepast. Het proces van het design van permeabele structuren is trial-and-error. Op basis van projectervaringen wordt veel geleerd en worden aanpassingen doorgevoerd.

Vraag 4: Wat zijn de beperkingen van de huidige ontwerpmethode van doorlatende constructies die worden gebruikt in mangroveherstelprojecten voor het effectief reguleren van golfenergie en golfhoogte?

Antwoord: De huidige ontwerpmethodes zijn afhankelijk van trial-and-error en expert judgement. Dit is inefficiënt.

Vraag 5: Hoe kom je bij het ontwerpen van een doorlatende structuur voor mangroveherstel aan de ontwerpgolfhoogte, waterdiepte en golfperioden en hoe groot zijn die ongeveer?

Antwoord: Voor het project in Demak zijn technische richtlijnen opgesteld vanuit het EcoShape-project, waarin bepaalde randvoorwaarden worden beschreven, zoals een maximale golfhoogte van 1 meter. Deze richtlijnen zijn belangrijk, maar het ontwerp is vaak meer afhankelijk van de getijslag dan van de golven zelf.

Vraag 6: Als je een waterdoorlatende constructie ontwerpt, met welke voorwaarden houd je dan rekening?

Antwoord: Bij het ontwerp houden we rekening met lokale omstandigheden, beschikbaarheid van lokale materialen, en traditionele bouwmethoden. De constructies moeten praktisch uitvoerbaar zijn en bestand zijn tegen dagelijkse en storm condities bestand zijn.

Vraag 7: Houdt u bij het ontwerpen van waterdoorlatende constructies rekening met dagelijkse of stormcondities?

Antwoord: Het ontwerp focust vooral op dagelijkse condities, omdat sedimentatie onder deze omstandigheden plaatsvindt. De structuren moeten echter ook bestand zijn tegen stormcondities, zodat ze niet worden vernield.

Vraag 8: Op welke leeftijd van mangroven wordt de doorlatende structuur gebaseerd?

Antwoord: De structuren zijn ontworpen om jonge mangroven van 2 tot 3 maanden oud te beschermen. Deze stekjes worden geplant en moeten gedurende één tot twee jaar beschermd worden. Daarna is geen bescherming meer nodig.

Vraag 9: Welke (doorgelaten) golfhoogte en golfenergieniveaus maken mangroveherstel in de eerste fase (1 tot 5 jaar) mogelijk?

Antwoord: De structuren moeten kleine golven van ongeveer 20-30 cm kunnen dempen, met af en toe heverigere golven. Deze condities zijn geschikt voor mangroveherstel in de eerste fase.

Vraag 10: Wat zijn volgens u de meest kritische factoren voor een permeabele structuur om effectief te zijn in het reguleren van golfenergie en golfhoogte voor mangroveherstel?

Antwoord: De materiaalkeuze is erg belangrijk. Zo heb gaat de voorkeur uit naar heel bamboe boven gespleten bamboe, vanwege de langere levensduur. Inspectie en onderhoud zijn vooral na stormen belangrijk om te voorkomen dat structuren kapot gaan.

Vraag 11: Het model bevat een aantal aannames en vereenvoudigingen met betrekking tot de regulering van golfenergie en golfhoogte. Welke kansen en risico's zie je per aanname/vereenvoudiging?

Antwoord: Het model neemt aan dat golven alleen loodrecht op de structuur afkomen. In de praktijk komen golven onder verschillende hoeken op de structuur af. Dit vermindert de energie. Het is belangrijk significante golfhoogte te gebruiken en niet alleen de pieken van golfhoogtes. Het model moet ook rekening houden met superpositie van golven. Dit geeft de realiteit beter weer.

Vraag 12: Denkt u dat een model dat de energieverdeling over de waterkolom laat zien, nuttig is voor het ontwerp van doorlatende constructies? Waarom wel of waarom niet?

Antwoord: Ja, een dergelijk model kan nuttig zijn voor het maken van ontwerpkeuzes. Het moet echter eenvoudig blijven om praktisch bruikbaar te zijn. Er moet niet teveel data nodig zijn.

Vraag 13: Welke eigenschappen zou het model moeten hebben om praktisch bruikbaar te zijn in het veld?

Antwoord: Het model moet zowel eenvoudige input data als output data nodig hebben, zodat het gemakkelijk kan worden vertaald naar een ontwerp.

Vraag 14: Wat maakt het aantrekkelijker om het model te gebruiken voor het ontwerpen van doorlatende constructies die golfenergie en golfhoogte reguleren?

Antwoord: Integratie in GIS applicaties zou het mogelijk maken om snel en effectief gebieden te analyseren voor de toepassing van doorlatende structuren. Bij een klik op de wereldkaart zou je dan al een model output kunnen genereren. Dit verhoogt de praktische bruikbaarheid en snelheid van besluitvorming. Daarvoor is het gebruik van open-source data wel nodig.

Vraag 15: Wat maakt het minder aantrekkelijk om het model te gebruiken?

Antwoord: Onduidelijkheid in het gebruik van de model output om ontwerpkeuzes te maken kan een nadeel zijn. Het moet voor de gebruiker duidelijk zijn hoe het model kan worden gebruikt om praktische en effectieve ontwerpen te kiezen en maken.

Vraag 16: Hoe waarschijnlijk is het dat u een dergelijk model zult gebruiken in uw ontwerp of onderzoek?

Antwoord: De kans is groot dat een dergelijk model gebruikt zal worden. Het vermindert de trial-and-error aanpak in een project. Als het model werkt, kan het een waardevolle aanvulling zijn voor mangroveherstelprojecten.

Datum: 08-04-2025
Expert: Ad Reniers
Taal: Nederlands

Vragen en Antwoorden

Vraag 1: Wat is uw expertise op het gebied van doorlatende constructies die worden gebruikt voor mangroveherstelprojecten, in het bijzonder met betrekking tot het reguleren van golfenergie en golfhoogte?

Antwoord: Mijn expertise ligt voornamelijk in het modelleren van semi-doorlatende constructies met betrekking tot golfmodellering en stromingsmodellering. Hierbij houdt ik mij bezig met aspecten zoals transmissie, demping, en reflectie van golven. We hebben hier in Delft veel experimenten gedaan om te kijken naar deze aspecten, vooral gericht op de afstand tussen structuren en hun dichtheid. Deze experimenten helpen bij het parametriseren en integreren van deze constructies in modellen. Daarnaast heb ik praktische ervaring opgedaan tijdens projecten in Indonesië. Dit in de Javazee bij Semarang en Demak. Hier heb ik me beziggehouden met onderzoek naar de effectiviteit van deze constructies.

Vraag 2: Waar heeft u deze expertise opgedaan?

Antwoord: Zoals aangegeven in Indonesië, maar ook in laboratoria.

Vraag 3: Hoe zou u de huidige manier van het ontwerpen van waterdoorlatende constructies en de verschillende ontwerpen die worden gebruikt in mangroveherstelprojecten beschrijven, in het bijzonder met betrekking tot de dissipatie van golfenergie en de reductie van golfhoogte?

Antwoord: Er zijn verschillende varianten van constructies, zoals palen met bushwood vulling. Echter, brushwood is niet stevig en verliest snel zijn effectiviteit. Daarom zoeken we naar alternatieven zoals het variëren van de dichtheid van palen, zowel in horizontale als verticale richting. Een uitdaging is dat de levensduur van constructies vaak te kort is voor effectief mangroveherstel, dat 5 tot 10 jaar kan duren. Veel constructies in Demak zijn binnen een of twee jaar kapot door stormcondities. Dit vraagt om robustere ontwerpen.

Vraag 4: Wat zijn de beperkingen van de huidige ontwerpmethode van doorlatende constructies die worden gebruikt in mangroveherstelprojecten voor het effectief reguleren van golfenergie en golfhoogte?

Antwoord: De grootste beperkingen zijn onder andere de korte levensduur van constructies en hun effectiviteit. Dieper geplaatste constructies ervaren grotere krachten en hebben een grotere kans op bezwijken. Ook de afstand tot de mangrove fringe is belangrijk. Een grote afstand vertraagt namelijk het plaatsvinden van sedimentatie.

Vraag 5: Hoe kom je bij het ontwerpen van een doorlatende structuur voor mangroveherstel aan de ontwerpgolfhoogte, waterdiepte en golfperioden en hoe groot zijn die ongeveer?

Antwoord: We gebruiken globale golfmodellen zoals ERA 5 om condities voor golfhoogte, periode, en richting te bepalen. Deze modellen bieden tijdseries waarmee kansverdelingen en extremen kunnen worden geanalyseerd.

Vraag 6: Als je een waterdoorlatende constructie ontwerpt, met welke voorwaarden houd je dan rekening?

Antwoord: Voorwaarden zoals verwachte levensduur en stormcondities zijn erg belangrijk. We moeten inschatten hoe lang een constructie effectief moet zijn. De structuur moet ontworpen zijn op return periodes van stormen. De keuze van materialen en bouwtechnieken spelen ook een grote rol.

Vraag 7: Houdt u bij het ontwerpen van waterdoorlatende constructies rekening met dagelijkse of stormcondities?

Antwoord: Er wordt rekening gehouden met stormcondities om te bepalen of een constructie de verwachte levensduur kan halen.

Vraag 8: Op welke leeftijd van mangroven wordt de doorlatende structuur gebaseerd?

Antwoord: Over het algemeen moet de structuur mangroven die erg jong zijn beschermen tot ze zonder structuur kunnen overleven.

Vraag 9: Welke (doorgelaten) golfhoogte en golfenergieniveaus maken mangroveherstel in de eerste fase (1 tot 5 jaar) mogelijk?

Antwoord: Een vermindering van de golfhoogte van ongeveer 50% is gewenst. Belangrijk is dat de structuur ruimte biedt voor sedimentatie. Dit is namelijk erg belangrijk voor effectief mangroveherstel.

Vraag 10: Wat zijn volgens u de meest kritische factoren voor een permeabele structuur om effectief te zijn in het reguleren van golfenergie en golfhoogte voor mangroveherstel?

Antwoord: De robuustheid van de structuur, een optimale demping van golven en genoeg aanvoer van sediment, en het minimaliseren van reflectie zijn ook erg belangrijk. Reflectie kan leiden tot erosie aan de zeewaartse kant van de structuur. Dit heeft invloed op de stabiliteit.

Vraag 11: Het model bevat een aantal aannames en vereenvoudigingen met betrekking tot de regulering van golfenergie en golfhoogte. Welke kansen en risico's zie je per aanname/vereenvoudiging?

Antwoord:

- **Het model gaat uit van alleen golven en laat stroming buiten beschouwing:** Stroming en verticaal getijde zijn belangrijk en moeten worden meegenomen.
- **Het model gaat uit van alleen reguliere golven en lineaire golftheorie en geen irreguliere golven:** Irreguliere golven en variaties in golfenergie moeten worden overwogen.
- **Het model gaat uit van golven die loodrecht op structuur afkomen:** Hoewel golven vaak loodrecht komen, zijn verschillende invalshoeken mogelijk. Daarentegen zijn loodrechte golven wellicht wel de maatgevende krachten, aangezien deze groter zijn dan golven die aankomen onder een hoek.
- **Het model rekent sedimenttransport niet door:** Wij rekenen dit wel door, want dan kan er iets gezegd worden over de morfodynamische ontwikkelingen.
- **Het model voert geen berekeningen aan de stabiliteit van de constructie uit:** Wij rekenen dit wel door, maar dat zou het model ook een stuk ingewikkelder maken.
- **Het model gaat uit van een vlakke zeebodem:** Een vlakke bodem is een vereenvoudiging. In werkelijkheid verschillende de bodemomstandigheden.

Vraag 13: Welke eigenschappen zou het model moeten hebben om praktisch bruikbaar te zijn in het veld?

Antwoord: Het model moet snel en eenvoudig rekenen en resultaten bieden die direct vertaald kunnen worden naar een ontwerp. Bij een aangenomen vlak zeebed, kan dit moeilijker zijn.

Vraag 14: Wat maakt het aantrekkelijker om het model te gebruiken voor het ontwerpen van doorlatende constructies die golfenergie en golfhoogte reguleren?

Antwoord: De snelheid van berekeningen en het snel inzicht kunnen geven in kritische condities maken het model aantrekkelijk. Het integreren van bestaande data en systemen kan de bruikbaarheid verder verhogen.

Vraag 15: Wat maakt het minder aantrekkelijk om het model te gebruiken?

Antwoord: De vereenvoudiging van complexe processen kan de nauwkeurigheid beïnvloeden. Het ontbreken van stabiliteitsanalyse en faalmechanismen kan een nadeel zijn.

Vraag 16: Hoe waarschijnlijk is het dat u een dergelijk model zult gebruiken in uw ontwerp of onderzoek?

Antwoord: Hoewel ik zelf meer gericht ben op complexere systemen en ruimtelijke variabiliteit, kan een snel en praktisch model nuttig zijn in het ontwerpproces.

Datum: 11 april 2025
Expert: Apri Astra
Taal: Engels

Questions and answers

Question 1: What is your expertise within permeable structures used for mangrove restoration projects, particularly in relation to regulating wave energy and wave height?

Answer: I don't have experience in designing permeable structures for mangrove restoration projects. As part of Wetlands International Indonesia, I communicate between project designers and implementers in the field. I focus on translating designs from our colleagues at Boskalis and Deltares to a practical implementation with local communities and contractors. I also conduct trainings to ensure proper construction of these structures.

Question 2: Where did you get this expertise?

Answer: I gained this expertise through my work with Wetlands International Indonesia. I have been actively involved in projects like those in Demak. I also collaborated with various stakeholders and gained local knowledge for effective implementation of the structures.

Question 3: How would you describe the current way of designing permeable structures and the varying designs used in mangrove restoration projects, especially in terms of wave energy dissipation and wave height reduction?

Answer: The current design process involves adapting designs to local conditions based on knowledge of stakeholders. Designs consist of two rows of main poles with a brushwood filling in between them. These structures proved to be less durable due to environmental factors like shipworm. Adjustments were made to use bamboo and stronger materials. This was often based on local community input.

Question 4: What are the limitations of the current design method of permeable structures used in mangrove restoration projects in effectively regulating wave energy and wave height?

Answer: The main limitation of the current design method is the durability of materials. Environmental conditions in Indonesia, such as dry and rainy seasons, affect the longevity of wood and bamboo. This reduces their effective lifespan to about three years instead of the intended five years. Ongoing maintenance is needed to ensure the structures continue to function as planned.

Question 5: When designing a permeable structure for mangrove restoration, where do you get the design wave height, water depth, and wave periods, and how big are those approximately? (Only for T. Wilms, A.Astra, J.Noordermeer)

Answer: While I am not directly involved in the design phase, the structures are calculated based on the highest expected wave heights. Tom Wilms or colleagues from Boskalis and Deltares would have more precise information on these parameters.

Question 6: When designing a permeable structure, what conditions apply do you take into account?

Answer: It is ensured that the structure allows water to flow through, especially during high tides. This way, sedimentation can take place.

Question 7: Do you take daily or storm conditions into account for the design of permeable structures?

Answer: Both daily and storm conditions are considered for the design of permeable structures. Normal high tide levels, with additional adjustments for higher tides during storms, are used to ensure sediment transport.

Question 8: At what age of mangroves will the permeable structure be based on?

Answer: The structures aim to support mangroves for up to five years, allowing them to grow and eventually take over the function of the permeable structures. In healthy conditions, mangroves can settle and grow.

Question 9: What (transmitted) wave height and wave energy levels make mangrove restoration in the first stage (1 till 5 years) possible?

Answer: The critical factor is the ability of the structures to trap sediment and protect it from being flushed away. This requires balancing wave energy dissipation with sediment deposition.

Question 10: In your opinion, what are the most critical factors for a permeable structure to be effective in regulating wave energy and wave height for mangrove restoration?

Answer: Effective sediment trapping and protection are crucial. The structures must stabilize sediment to provide a substrate for mangroves to grow while also dissipating wave energy to prevent erosion.

Question 11: The model created contains some assumptions and simplifications related to wave energy and wave height regulation. What are the opportunities and risks you see per assumption/simplifications? (see table X, Appendix X)

Answer:

- **The model assumes that only waves occur:** Including tidal effects is important as they are important for sediment transport.

- **The model assumes only regular waves to occur:** In real conditions irregular waves also occur.
- **The model assumes linear wave theory to occur:** In reality are also non-linear effects important.
- **The model assumes waves to approach the structure perpendicular:** Waves might approach from varying angles.
- **The model does provide calculations on sediment transport:** Sediment dynamics are quite important for mangrove restoration.
- **The model assumes an even seabed:** Variability in seabed conditions affects wave behavior.
- **The model does not take stability of the structure into account:** In reality, structural stability is importantl, especially during storms.
- **The model does only assume horizontal elements:** Both horizontal and vertical elements are important for structural integrity.

Question 12: Do you believe that a model which shows the energy distribution over the water column so it is known where energy should be reflected or dissipated to meet a transmitted wave energy/height is beneficial for the design of permeable structures? Why or why not?

Answer: Yes, such a model would be beneficial, since it would provide insights into optimal design and placement of structures. This will help to effectively manage wave energy and support sediment transport.

Question 13: What characteristics should the model have to be practically useful in the field, specifically for regulating wave energy and wave height?

Answer: The model should be understandable and usable for local communities and stakeholders. It should clearly show steps and necessary inputs to be of practical use.

Question: What makes it more attractive to use the model for designing permeable structures that regulate wave energy and wave height?

Answer: The model's ability to show successful sediment trapping and mangrove restoration would make it attractive.

Question 15: What makes it less attractive to use the model for designing permeable structures that regulate wave energy and wave height?

Answer: If the model can not account for local variability or practical challenges, it may be less effective.

Question 16: How likely are you to use such a model in your design or research, particularly for projects focused on mangrove restoration and protection against erosion?

Answer: Very likely, as it could improve our ability to design projects without companies as Witteveen+Bos and Deltares. It furthermore helps to address erosion challenges effectively across different locations in Indonesia.

Datum: 14 april 2025
Expert: Tom Wilms
Taal: Nederlands

Vragen en Antwoorden

Vraag 1: Wat is uw expertise op het gebied van doorlatende constructies die worden gebruikt voor mangroveherstelprojecten, in het bijzonder met betrekking tot het reguleren van golfenergie en golfhoogte?

Antwoord: Ik heb expertise in het aanleggen van permeabele dammen in Indonesië en daarnaast met het opstellen van richtlijnen voor het ontwerp van dergelijke structuren. Er is een gebrek is aan tools om deze dammen effectief te ontwerpen, waardoor ze vaak over gedimensioneerd zijn.

Vraag 2: Waar heeft u deze expertise opgedaan?

Antwoord: Deze expertise heb ik voornamelijk opgedaan in Indonesië. Voor mijn tijd daar had ik nog nooit van doorlatende dammen gehoord. Mijn expertise is gebaseerd op praktijkervaring en tekeningen van eerdere projecten die gebaseerd waren op Nederlandse ontwerpen.

Vraag 3: Hoe zou u de huidige manier van het ontwerpen van waterdoorlatende constructies en de verschillende ontwerpen die worden gebruikt in mangroveherstelprojecten beschrijven, in het bijzonder met betrekking tot de dissipatie van golfenergie en de reductie van golfhoogte?

Antwoord: De huidige ontwerpen zijn gebaseerd op wat in Nederland werd gemaakt, zoals projecten in de Waddenzee. Een voorbeeld is een structuur dat bestaat uit palenrijen met takkenbossen ertussen. In de afgelopen 10 tot 15 jaar is er meer gekeken naar andere ontwerpen. Hiervoor is in de paper van Han Winterwerp ook een overzicht te vinden. Er is veel vooruitgang geboekt door te doen, maar nog niet door te analyseren.

Vraag 4: Wat zijn de beperkingen van de huidige ontwerpmethode van doorlatende constructies die worden gebruikt in mangroveherstelprojecten voor het effectief reguleren van golfenergie en golfhoogte?

Antwoord: De ontwerpen zijn gebaseerd op uitvoeringservaring en zijn soms overgedimensioneerd of te dun, waardoor ze snel kapot gaan. Er wordt niet specifiek gekeken naar de omgeving, golfbelastingen, getij, of grondsoort. Het huidige ontwerp is vaak trial-and-error.

Vraag 5: Hoe kom je bij het ontwerpen van een doorlatende structuur voor mangroveherstel aan de ontwerpgolfhoogte, waterdiepte en golfperioden en hoe groot waren die ongeveer in Demak?

Antwoord: Waterstanden en golfhoogtes en golfperiodes zijn niet zelf afgeleid. Er wordt gebruik gemaakt van bestaande informatie van vorige projecten. Gegevens kwamen ook uit scheepvaartgegevens van de haven in de buurt en open-source data.

Vraag 6: Als je een waterdoorlatende constructie ontwerpt, met welke voorwaarden houd je dan rekening?

Antwoord: Er zijn geen concrete voorwaarden waar rekening mee wordt gehouden. Meestal worden twee palenrijen met takkenbossen ertussen gebruikt. De kracht op deze constructies werd echter wel groot. Daardoor werden constructies scheef gedrukt.

Vraag 7: Houdt u bij het ontwerpen van waterdoorlatende constructies rekening met dagelijkse of stormcondities?

Antwoord: Dagelijkse condities zijn belangrijker omdat ze vaker voorkomen dan stormcondities. Het is verder belangrijk dat erosie wordt voorkomen en dat er sedimentaanvoer is. Er is behoefte aan een analyse van erosie bij verschillende belastingen om beter inzicht te krijgen. Maar het moet wel nog een mix van beide blijven.

Vraag 8: Op welke leeftijd van mangroven wordt de doorlatende structuur gebaseerd?

Antwoord: Structuren moeten zorgen voor goede condities voor sedimentatie voordat mangroves kunnen terugkeren. Jonge mangroves zijn nog niet sterk en kunnen weggespoeld worden. Zodra mangroves bijvoorbeeld 2-3 meter hoog zijn of 2-3 jaar oud, kunnen ze meer belastingen aan.

Vraag 9: Welke (doorgelaten) golfhoogte en golfenergieniveaus maken mangroveherstel in de eerste fase (1 tot 5 jaar) mogelijk?

Antwoord: Er is geen specifiek getal, maar een kansverdeling kan inzicht geven.

Vraag 10: Wat zijn volgens u de meest kritische factoren voor een permeabele structuur om effectief te zijn in het reguleren van golfenergie en golfhoogte voor mangroveherstel?

Antwoord: De kritische factoren zijn de belasting die de constructie kan weerstaan en ervoor zorgen dat sediment blijft. De structuur moet effectief zijn in het dempen van golven en het faciliteren van sedimentaanvoer.

Vraag 11: Het model bevat een aantal aannames en vereenvoudigingen met betrekking tot de regulering van golfenergie en golfhoogte. Welke kansen en risico's zie je per aanname/vereenvoudiging?

Antwoord:

- **Het model gaat uit van alleen golven en laat stroming buiten beschouwing:** Stromingen worden niet meegenomen. Deze zouden wat verdieping kunnen toevoegen. Voor nu is het voldoende om alleen golvenmee te nemen.

- **Reguliere golven:** Het gebruik van een spectrum van golven is realistischer, maar de huidige versimpeling is voldoende.
- **Lineaire golftheorie:** Dit is een goede basis, maar dit kan verbeterd worden door ook energie in de golftop te bekijken.
- **Het model gaat uit van golven die loodrecht op structuur afkomen:** Golven draaien vaak bij in ondiepe gebieden, dus invallende hoeken kunnen anders zijn.
- **Het model rekent sedimenttransport niet door:** Effectiviteit van constructies kan beïnvloed worden door sedimenttransport.
- **Het model gaat uit van een vlakke zeebodem:** Taluds zijn vaak flauw, dus het aannemen van een vlakke bodem is een redelijke vereenvoudiging.
- **Het model rekent de stabiliteit van de structuur niet door:** Werkende belastingen en krachten moeten worden berekend om stabiliteit van de structuur te garanderen.

Vraag 12: Denkt u dat een model dat de energieverdeling over de waterkolom laat zien, zodat bekend is waar energie moet worden gereflecteerd of afgevoerd om te voldoen aan een doorgegeven golfenergie/hoogte, nuttig is voor het ontwerp van doorlatende constructies? Waarom wel of waarom niet?

Antwoord: Ja, dit kan inzicht geven in de energieverdeling en helpen bij het bepalen van de optimale locaties voor constructies en het ontwerp ervan.

Vraag 13: Welke eigenschappen zou het model moeten hebben om praktisch bruikbaar te zijn in het veld, specifiek voor het reguleren van golfenergie en golfhoogte?

Antwoord: Het model moet eenvoudig te gebruiken zijn. Waterstanden waterstanden, bodemgegevens, en golfcondities moeten makkelijk kunnen worden ingevoerd. Het moet ook snel oplossingen geven voor verschillende scenario's.

Vraag 14: Wat maakt het aantrekkelijker om het model te gebruiken voor het ontwerpen van doorlatende constructies die golfenergie en golfhoogte reguleren?

Antwoord: Het model moet krachtinformatie geven en visueel duidelijk zijn. Het moet makkelijk zijn om gegevens in te laden en direct ontwerpopties te genereren. Het zou ook in het veld gebruikt moeten kunnen worden om direct ontwerpen te maken.

Vraag 15: Wat maakt het minder aantrekkelijk om het model te gebruiken voor het ontwerpen van doorlatende constructies die golfenergie en golfhoogte reguleren?

Antwoord: Als er veel handmatige stappen nodig zijn of veel zelf uitgezocht moet worden, kan het minder aantrekkelijk zijn. Het moet snel en efficiënt werken zonder veel handwerk.

Vraag 16: Hoe waarschijnlijk is het dat u een dergelijk model zult gebruiken in uw ontwerp of onderzoek, in het bijzonder voor projecten gericht op mangroveherstel en bescherming tegen erosie?

Antwoord: Zeer waarschijnlijk, aangezien het model bruikbaar is voor projecten in Indonesië, Demak, en mogelijk andere locaties wereldwijd, zoals Nieuw-Caledonië en Latijns-Amerika. Het biedt waardevolle inzichten en kan helpen bij het verbeteren van de ontwerpfase.

Datum: 16 april 2025
Expert: Gert Klopman
Taal: Nederlands

Vragen en Antwoorden

Vraag 1: Wat is uw expertise op het gebied van doorlatende constructies die gebruikt worden voor mangroveherstelprojecten, in het bijzonder met betrekking tot het reguleren van golfenergie en golfhoogte?

Antwoord: Mijn expertise ligt in het werk dat ik heb gedaan in Indonesië. Dit was met name in samenwerking met de Universiteit van Yogyakarta, waar we bezig waren met bamboe constructies voor mangroveherstel. Daarnaast heb ik bij Witteveen en Bos gewerkt aan doorlatende constructies in verschillende omgevingen.

Vraag 2: Waar heeft u deze expertise opgedaan?

Antwoord: Deze expertise heb ik opgedaan in Indonesië en bij Witteveen en Bos.

Vraag 3: Hoe zou u de huidige manier van het ontwerpen van waterdoorlatende constructies en de verschillende ontwerpen die worden gebruikt in mangroveherstelprojecten beschrijven?

Antwoord: Ik heb geen ervaring met de huidige ontwerpmethode van deze structuren, dus ik kan daar geen informatie over geven.

Vraag 4: Wat zijn de beperkingen van de huidige ontwerpmethode van doorlatende constructies die worden gebruikt in mangroveherstelprojecten?

Antwoord: Zonder details over de huidige methode kan ik hier geen goed antwoord op geven. Destijds werden laboratoriumproeven gedaan om de effectiviteit van verschillende ontwerpen te testen, zoals de dissipatie van golfenergie en de reductie van golfhoogte.

Vraag 5: Hoe kom je bij het ontwerpen van een doorlatende structuur voor mangroveherstel aan de ontwerpgolfhoogte, waterdiepte en golfperioden?

Antwoord: In Indonesië zijn er weinig metingen beschikbaar, dus we maken gebruik van wereldwijde windgegevens en modellen zoals ECMWF. We gebruiken numerieke modellen zoals Swan om golfdata van offshore naar nearshore om te vormen.

Vraag 6: Als je een waterdoorlatende constructie ontwerpt, met welke voorwaarden houd je dan rekening?

Antwoord: We houden rekening met de criteria voor wat we willen beschermen, zoals de sterkte van mangroves of schepen. Hierbij horen het bepalen van de kans op extreme condities en eisen voor weerstand en sterkte van de constructies.

Vraag 7: Houdt u bij het ontwerpen van waterdoorlatende constructies rekening met dagelijkse of stormcondities?

Antwoord: We richten ons meer op extreme condities zoals stormen die een of enkele keren per jaar voorkomen, en soms op stormen met een terugkeer van 5 jaar.

Vraag 8: Op welke leeftijd van mangroven wordt de doorlatende structuur gebaseerd?

Antwoord: Dit hangt af van de grootte van de mangroves bij aanplant, maar specifieke details daarover kan ik me niet herinneren.

Vraag 9: Welke (doorgelaten) golfhoogte en golfenergieniveaus maken mangroveherstel in de eerste fase (1 tot 5 jaar) mogelijk?

Antwoord: Dit weet ik niet precies. Het hangt sterk af van de bodemstructuur en de erosie eigenschappen van het gebied waar mangroves zich bevinden.

Vraag 10: Wat zijn volgens u de meest kritische factoren voor een permeabele structuur om effectief te zijn in het reguleren van golfenergie en golfhoogte voor mangroveherstel?

Antwoord: De transmissie van golven door de structuur en de weerstand van de constructie tegen verschillende belastingen zijn erg belangrijk. Ook de stabiliteit van de constructie is belangrijk.

Vraag 11: Het model bevat een aantal aannames en vereenvoudigingen met betrekking tot de regulering van golfenergie en golfhoogte. Welke kansen en risico's zie je per aanname/vereenvoudiging?

Antwoord:

- **Het model gaat uit van alleen golven en laat stroming buiten beschouwing:** Het is vaak voldoende om alleen golven te mee te nemen, maar stromingen kunnen ook invloed hebben op waterstandsverschillen.
- **Het model gaat uit van reguliere golven:** Dit is gebruikelijk in de ontwerppraktijk, maar moet gekoppeld worden aan een strategie voor ontwerpstormen.
- **Het model gaat uit van lineaire golftheorie:** Dit is een goede basis, maar niet altijd representatief voor alle omstandigheden.
- **Het model rekent sedimenttransport niet door:** Dit is belangrijk voor stabiliteit van de constructie en mangroves.
- **Het model gaat uit van een vlakke zeebodem:** Dit is een ralistische vereenvoudiging.
- **Het model rekent de stabiliteit van de structuur niet door:** Dit is eigenlijk wel essentieel om rekening mee te houden, vooral bij hoge belastingen.

Vraag 12: Denkt u dat een model dat de energieverdeling over de waterkolom laat zien, zodat bekend is waar energie moet worden gereflecteerd of afgevoerd

om te voldoen aan een doorgegeven golfenergie/hoogte, nuttig is voor het ontwerp van doorlatende constructies? Waarom wel of waarom niet?

Antwoord: Ja, het zou nuttig zijn om een beter inzicht te krijgen in de doorlatendheid en reductie van golfhoogte.

Vraag 13: Welke eigenschappen zou het model moeten hebben om praktisch bruikbaar te zijn in het veld?

Antwoord: Het model moet eenvoudig zijn, bijvoorbeeld via een Python-programma of Excel-sheet. Daarnaast moet het makkelijke verkrijgbare input gebruiken.

Vraag 14: Wat maakt het aantrekkelijker om het model te gebruiken voor het ontwerpen van doorlatende constructies die golfenergie en golfhoogte reguleren?

Antwoord: Het model zou een grote verbetering zijn ten opzichte van trial-and-error methodes die nu wordt gebruikt. Dit vooral door duidelijke richtlijnen te geven het ontwerp.

Vraag 15: Wat maakt het minder aantrekkelijk om het model te gebruiken voor het ontwerpen van doorlatende constructies die golfenergie en golfhoogte reguleren?

Antwoord: Gebruikersgemak is erg belangrijk. Als gebruikers zelf op zoek moeten naar data, kan dat de aantrekkelijkheid verminderen.

Vraag 16: Hoe waarschijnlijk is het dat u een dergelijk model zult gebruiken in uw ontwerp of onderzoek?

Antwoord: Zeer waarschijnlijk, omdat het een handige tool zou zijn voor het ontwerp van mangroveherstelprojecten.

Datum: 23 april 2025
Expert: Erik Horstman
Taal: Nederlands

Vragen en Antwoorden

Vraag 1: Wat is uw expertise op het gebied van doorlatende constructies die gebruikt worden voor mangroveherstelprojecten, in het bijzonder met betrekking tot het reguleren van golfenergie en golfhoogte?

Antwoord: Ik heb vooral expertise in natuurlijke mangroves, zonder het gebruik van doorlatende structuren. Ik heb gewerkt in gebieden zoals Singapore, Nieuw-Zeeland, Thailand en de Cariben. In Singapore heb ik structuren gezien die erosie tegengaan, zoals een soort wand van palmstokken, maar ik heb zelf geen ontwerp ervaring met deze structuren.

Vraag 2: Waar heeft u deze expertise opgedaan?

Antwoord: Mijn ervaring komt van werk in verschillende landen met natuurlijke mangroves: Singapore, Nieuw-Zeeland, Thailand en in het Caribisch gebied.

Vraag 3: Hoe zou u de huidige manier van het ontwerpen van waterdoorlatende constructies en de verschillende ontwerpen die worden gebruikt in mangroveherstelprojecten beschrijven?

Antwoord: De ontwerpen lijken vaak ad hoc te zijn. Gemaakt zonder vaste richtlijnen. Ze zijn gebaseerd op lokale condities en lokaal beschikbare materialen, zoals bamboe. Er is geen standaard ontwerpfilosofie. Het is eigenlijk een trial-and-error aanpak.

Vraag 4: Wat zijn de beperkingen van de huidige ontwerpmethode van doorlatende constructies die worden gebruikt in mangroveherstelprojecten?

Antwoord: Het gebrek aan concrete richtlijnen is een belangrijke beperking in het ontwerpproces van doorlatende constructies. Er is behoefte voor methoden die de ideale omstandigheden voor mangrovevestiging vergelijken met lokale condities, zodat duidelijk is welke ingrepen nodig zijn om hieraan te kunnen voldoen.

Vraag 5: Hoe kom je bij het ontwerpen van een doorlatende structuur voor mangroveherstel aan de ontwerpgolfhoogte, waterdiepte en golfperioden?

Antwoord: Hoewel ik deze gegevens niet zelf gebruik, zijn er papers die thresholds en richtlijnen bieden.

Vraag 6: Als je een waterdoorlatende constructie ontwerpt, met welke voorwaarden houd je dan rekening?

Antwoord: Je moet rekening houden met de voorwaarden die in papers beschreven worden, zoals de hydrodynamische thresholds voor mangrovevestiging.

Vraag 7: Houdt u bij het ontwerpen van waterdoorlatende constructies rekening met dagelijkse of stormcondities?

Antwoord: Dagelijkse condities zijn leidend bij het ontwerpen. Hierbij dient een doorkijk naar stormcondities te worden gemaakt. Stormen kunnen sediment aanvoeren, wat gunstig kan zijn, dus die wil je niet volledig tegenhouden.

Vraag 8: Op welke leeftijd van mangroven wordt de doorlatende structuur gebaseerd?

Antwoord: Structuren zijn vooral van belang in de vestigingsfase van mangroves, omdat ze dan het meest kwetsbaar zijn. Na enkele jaren kunnen mangroves zelf golven dempen en stabiliteit bieden.

Vraag 9: Welke (doorgelaten) golfhoogte en golfenergieniveaus maken mangroveherstel in de eerste fase (1 tot 5 jaar) mogelijk?

Antwoord: Dit is moeilijk te bepalen, omdat het afhangt van de waterstand en bathymetrie. De kritische bodemschuifspanning mag niet groter zijn dan de worteldiepte van de mangrove.

Vraag 10: Wat zijn volgens u de meest kritische factoren voor een permeabele structuur om effectief te zijn in het reguleren van golfenergie en golfhoogte voor mangroveherstel?

Antwoord: De hoogte van de structuur en zijn permeabiliteit zijn erg belangrijk. De structuur moet golven effectief dempen zonder te permeabel te zijn.

Vraag 11: Het model bevat een aantal aannames en vereenvoudigingen met betrekking tot de regulering van golfenergie en golfhoogte. Welke kansen en risico's zie je per aanname/vereenvoudiging?

Antwoord:

- **Het model gaat uit van alleen golven en laat stroming buiten beschouwing:** Dit heeft het risico is dat de vestigingsperiode voor mangroves niet wordt meegenomen.
- **Reguliere golven:** Deze aanname is vaak gemaakt, maar de variatie in golven moet goed worden gekozen.
- **Lineaire golftheorie:** Dit kan onzekerheden in de voorspelling van krachten op structuren geven.
- **Het model gaat uit van golven die loodrecht op structuur afkomen:** Dit is wel het worst-case scenario, wat veilig is.
- **Het model rekent sedimenttransport niet door:** Sedimenttransport is belangrijk voor bodemhoogteveranderingen en moet in een ruimtelijk model worden meegenomen.

- **Het model gaat uit van een vlakke zeebodem:** Neemt ruwheid van de bodem dan niet mee, wat invloed kan hebben op golven.
- **Het model rekent de stabiliteit van de structuur niet door:**

Vraag 12: Denkt u dat een model dat de energieverdeling over de waterkolom laat zien, zodat bekend is waar energie moet worden gereflecteerd of afgevoerd om te voldoen aan een doorgegeven golfenergie/hoogte, nuttig is voor het ontwerp van doorlatende constructies? Waarom wel of waarom niet?

Antwoord: Ja, het is nuttig om inzicht te krijgen in hoe effectief structuren zijn en hoe ze verder geoptimaliseerd kunnen worden.

Vraag 13: Welke eigenschappen zou het model moeten hebben om praktisch bruikbaar te zijn in het veld?

Antwoord: Het model moet eenvoudig data kunnen gebruiken. Zoals het kustprofiel, de getijslag en het golfklimaat. Het model moet ook gemakkelijk aanpasbaar zijn naar lokale omstandigheden.

Vraag 14: Wat maakt het aantrekkelijker om het model te gebruiken voor het ontwerpen van doorlatende constructies die golfenergie en golfhoogte reguleren?

Antwoord: Het gebruik van een gestandaardiseerde input maakt het gebruik van het model aantrekkelijker. Je moet met behulp van het model ook gemakkelijk verschillende ontwerpen te kunnen vergelijken.

Vraag 15: Wat maakt het minder aantrekkelijk om het model te gebruiken?

Antwoord: Als er veel lokale data nodig is, kan dat de bruikbaarheid van het model verminderen. Complexe aanpassingen aan het model kunnen ook een probleem zijn voor gebruikers.

Vraag 16: Hoe waarschijnlijk is het dat u een dergelijk model zult gebruiken in uw ontwerp of onderzoek?

Antwoord: Het hangt af van toekomstige onderzoeksprojecten. Het model biedt belangrijke inzichten, maar de directe toepassing is afhankelijk van verdere ontwikkeling en financiering.