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LABORATORY EXPERIMENTS ON HYDRODYNAMIC PERFORMANCES OF MANGROVE FOREST AGAINST TSUNAMI IMPACT

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ABSTRACT

Laboratory experiments on the damping performance of coastal forest under tsunami and storm wave conditions were performed in the twin-wave flume of Leichtweiss-Institute, TU Braunschweig, Germany. The parameterization of the mangroves (*Rhizophora* sp.) was based on the stiff structure assumption using field data and the concept of submerged root volume ratio. The effect of the forest width, water depth conditions and incident wave characteristics on wave attenuation was investigated. The modes of wave evolution on the foreshore, particularly the breaking wave conditions, were found to influence the attenuation performance of the forest. The reduction of the forces exerted by solitary waves on the single trees along the forest was first considered as a measure for the tsunami damping. The minimum force transmission coefficient was observed for waves broken at the smallest water depth and yielded about 0.14-0.20.

Introduction

The mechanisms and effectiveness of wave attenuation by coastal forest still remain one of the unknown aspects in coastal science. Due to the capability of coastal vegetation to attenuate storm waves and storms, green belts are widely used as a protection along shores. However, its performance under extreme events such as a tsunami is questionable when recalling the experience from the 2004 Indian Tsunami event (e.g. Harada and Tanaka 2005, EJF 2006, Asano 2008). The contradictory post-tsunami surveys indicated a significant importance of such aspects as vegetation

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type, density, age and general health conditions on the damping characteristic. Moreover, the influence of the local bathymetry and topography, soil conditions and tsunami transformation onshore should be additionally considered. Prediction of the damping performance of coastal forest together with forest control-growth would allow to provide a more efficient and an environmentally friendly coastal protection. Therefore, extensive and systematic studies combining both laboratory experiments, numerical modelling and field data have been undertaken in the framework of the *Tsunami Attenuation Performance by Coastal Forests* (TAPFOR) project. The first results on coastal forest parameterization and laboratory experiments are discussed in this paper.

1 Parameterization of coastal forest

In this study, mangrove species are considered as the most representative type of coastal vegetation to be found in swampy-beach habitats of the regions exposed to tsunami hazard. Taking into account species occurrence as well as their features conditioning the wave damping performance (e.g. root system), *Rhizophora* sp. was selected for a further analysis (see Fig. 1a). According to the field surveys after the 2004 and 2006 tsunami events, only mangrove roots and trunks remained intact, while canopies experienced serious damage (e.g. Yanagisawa et al. 2009). Therefore, a stiff structure assumption was applied first to the tree parameterization procedure, in which a mangrove root system and a trunk were considered only (without a canopy). In this case, which corresponds to the impact of waves lower than the canopy, the parameters to be taken into account in the parameterization process are: (i) root structure (width W_R, total height h_R, submergence h_{SB}, diameter D_R) and (ii) trunk strength (diameter at breast D_{dbh}, height h_T) (see Fig. 1b). In the future analysis, a concept of a flexible tree assumption will be examined as a next step, where all tree structural parts (i.e. roots, trunk and canopy) are exposed to wave attack. Since the tree age determines the vegetation resistance to wave attack (resulting in tree breaking or uprooting), a mature mangrove tree was considered, with the typical dimensions for this evolution stage shown in Fig. 1b (Husrin and Oumeraci 2009a and b).

a) *Rhizophora* sp. in its habitat   b) Definition sketch of mangrove tree

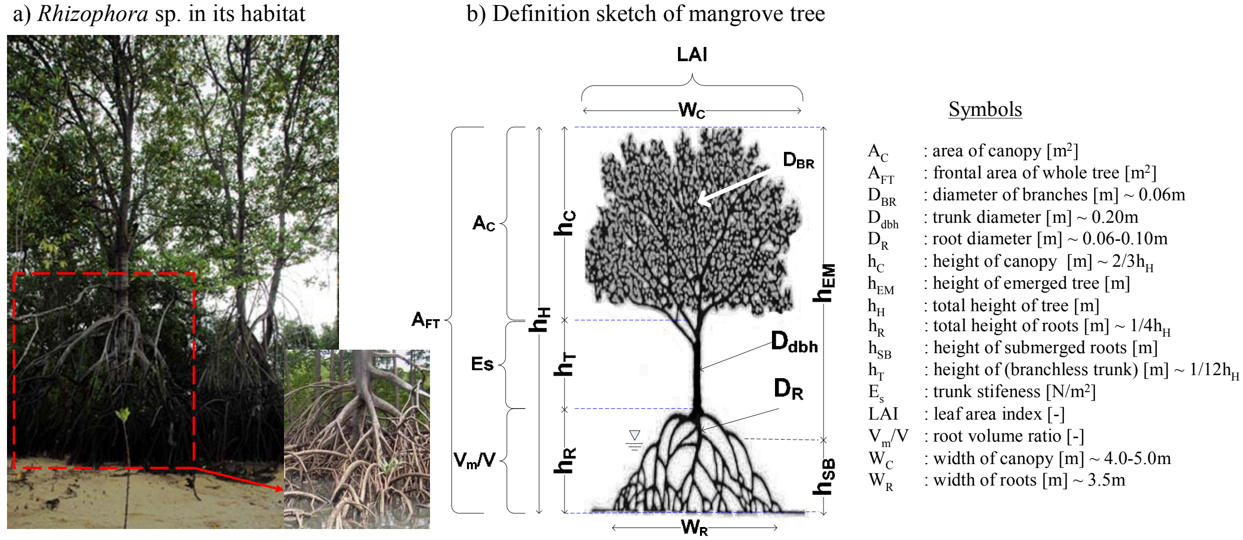

Figure 1. Characteristic of representative mangrove tree (*Rhizophora* sp.).

Parameterization of a mangrove tree was based on the field measurements of mangrove dimensions (Istiyanto et al. 2003) and a concept of a submerged root volume ratio V_m/V

introduced by Mazda et al. 1997 for different mangrove species in Japan and Australia (with V_m representing the total submerged volume of roots and V the control volume of water, as illustrated in Fig. 2a). The latter indicates the changes of the root volume with water depth h (see Fig. 2b).

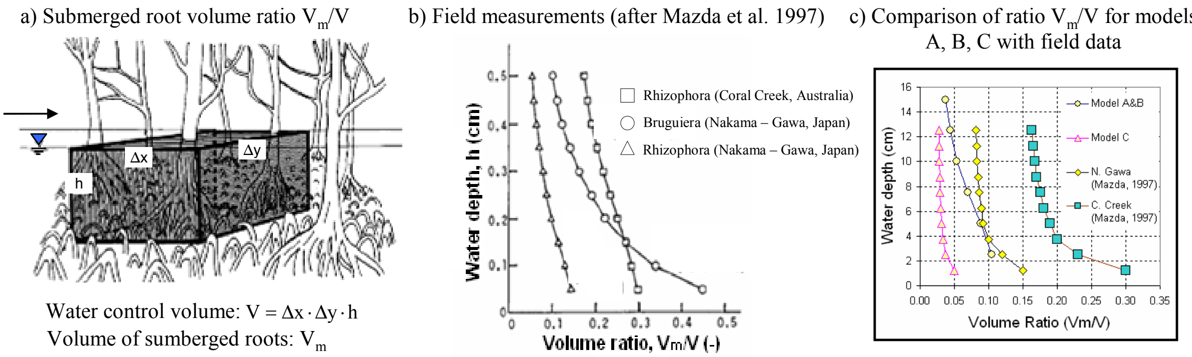

Figure 2. Definition of submerged root volume ratio V_m/V (adapted from Husrin and Oumeraci 2009a)

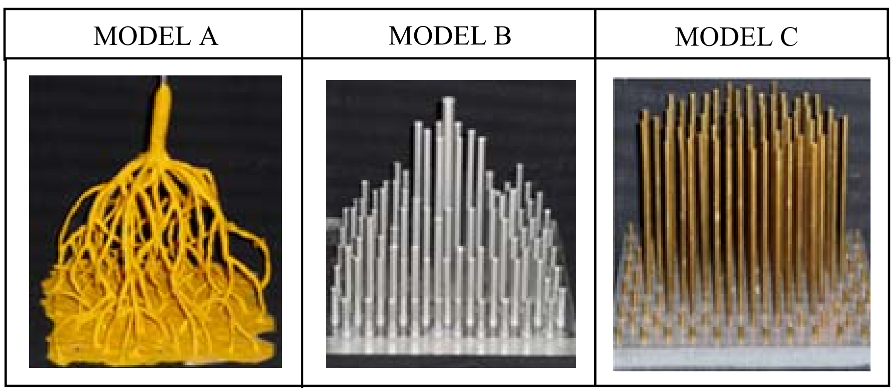

Figure 3. Real mangrove (model A) and parameterized models B and C (adapted from Husrin and Oumeraci 2009a)

Three mangrove models were constructed at scale 1:20 (see Fig. 3) and tested in a flume of the Leichtweiss-Institute (LWI) at TU Braunschweig, Germany to determine their properties under steady flow conditions (with velocity range 0.5-1.0 m/s and different water depths 0.5-1.25 m). Model A represents a real mangrove tree with a complex root system. Model B and model C represent the parameterized mangrove trees, with the root system and the trunk constructed using cylinders of a given height and diameter. The cylinders were arranged into a staggered and a tandem system to investigate the effect of the model frontal area on flow properties (for details see Husrin and Oumeraci 2009a). The resultant submerged root volume ratio V_m/V is similar for the models A and B. For the model C it is however much reduced in comparison to the prototype by Mazda et al. (1997) due to technical feasibility (see Fig. 2c).

On the basis of the comparative analysis of the model properties and the experimental results (i.e. the ratio V_m/V, water head difference behind model, reduction of flow velocities and exerted forces), model B with the staggered arrangement was selected for further investigation on the damping performance of mangrove forest performed in the wave flume (for details see Husrin and Oumeraci 2009a).

2 Experimental set-up, measuring techniques and testing programme

Model tests on the damping performance of mangrove forest were conducted at scale 1:25 in the twin-wave flumes of LWI that are approximately 90m long and 1.2m high. The flumes are equipped at the one end in a wave maker capable of generating waves synchronically in both flumes and a rubble mound wave absorber at the other end. A beach platform of height h_r=0.415m with the mangrove forest model was constructed in the 2m wide flume at a distance of 23.64m from the wave maker. The same platform, however without the forest, was placed in the 1m wide flume (see Figs. 4 and 5d). The beach platform consists of a frontal slope circa 1:20 that elongates into a horizontal part with the mangrove models.

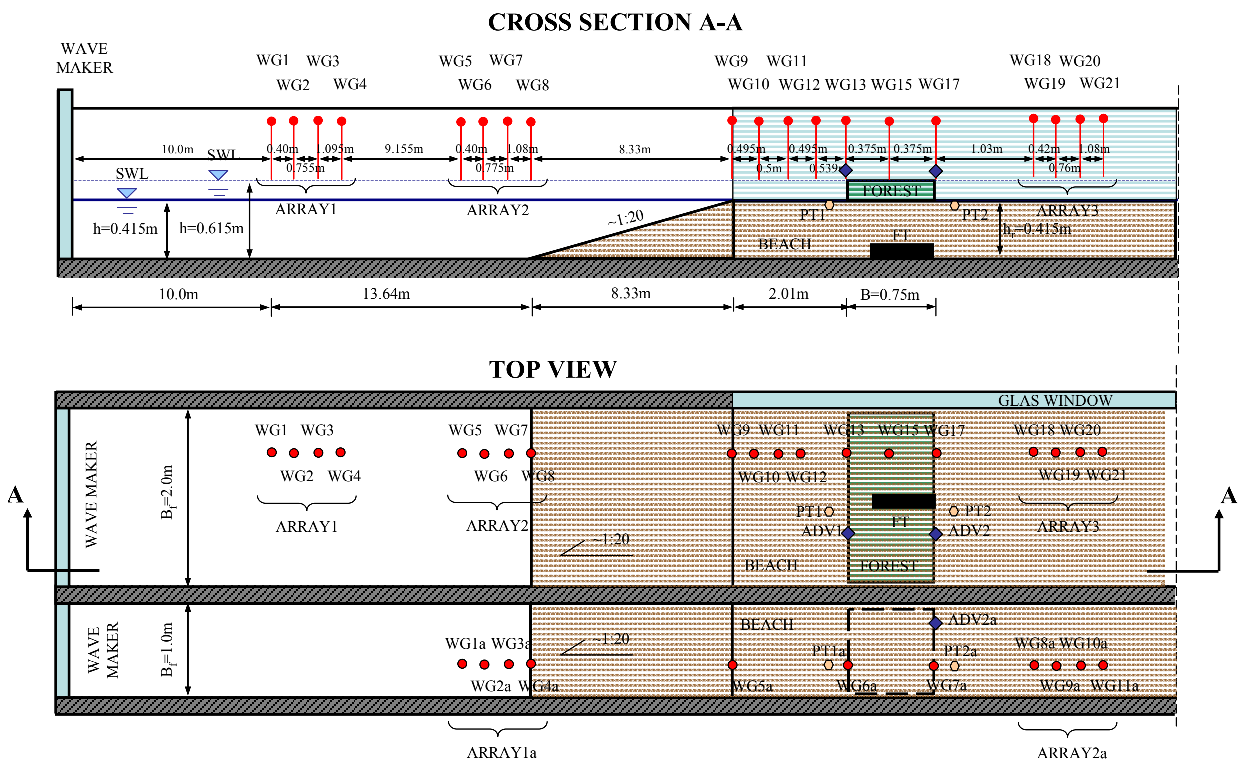

Figure 4. Exemplary experimental set-up in twin-wave flumes of LWI (B=0.75m)

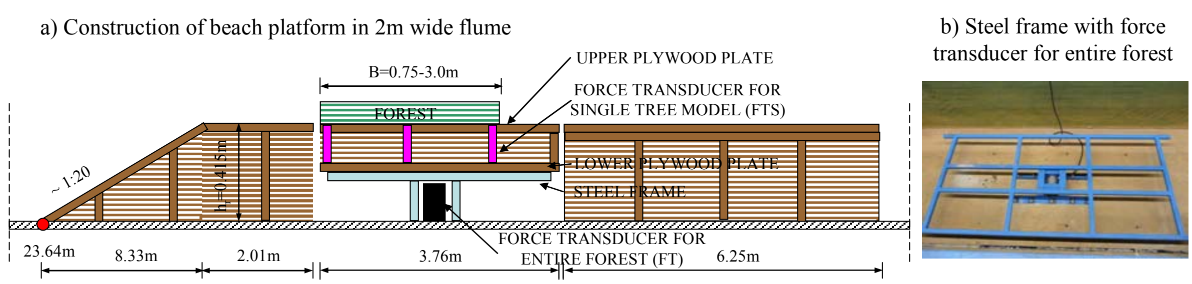

Figure 5. Moveable system measuring forces exerted on entire forest and single tree model

The following data is obtained from the tests which are synchronically performed in the twin-wave flumes: (i) water free surface elevation measured by 32 wave gauges (WG), arranged generally in wave gauge arrays to perform the wave reflection analysis for storm waves (see Fig. 4), (ii) forces exerted on entire forest measured by a force transducer FT (see Figs. 4 and 5b),

(iii) forces exerted on single tree models measured by 10 force transducers FTS (see Figs. 5a and 6a), (iv) pressure measured by 4 pressure transducers (PT) located in front of and behind the forest (see Fig. 4), (v) flow velocities measured by 3 acoustic Doppler velocimeters (ADV) installed in front of and behind the forest (see Fig. 4). Video cameras were used additionally to record wave propagation in both flumes.

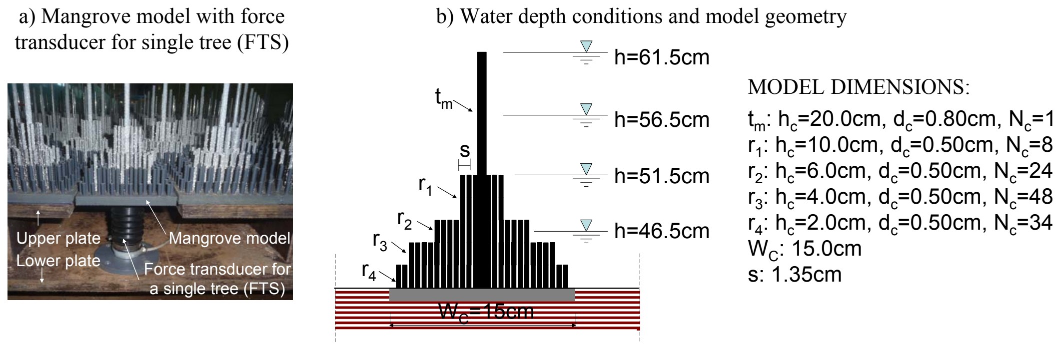

Figure 6. Construction details of mangrove model in relation to water depth conditions tested

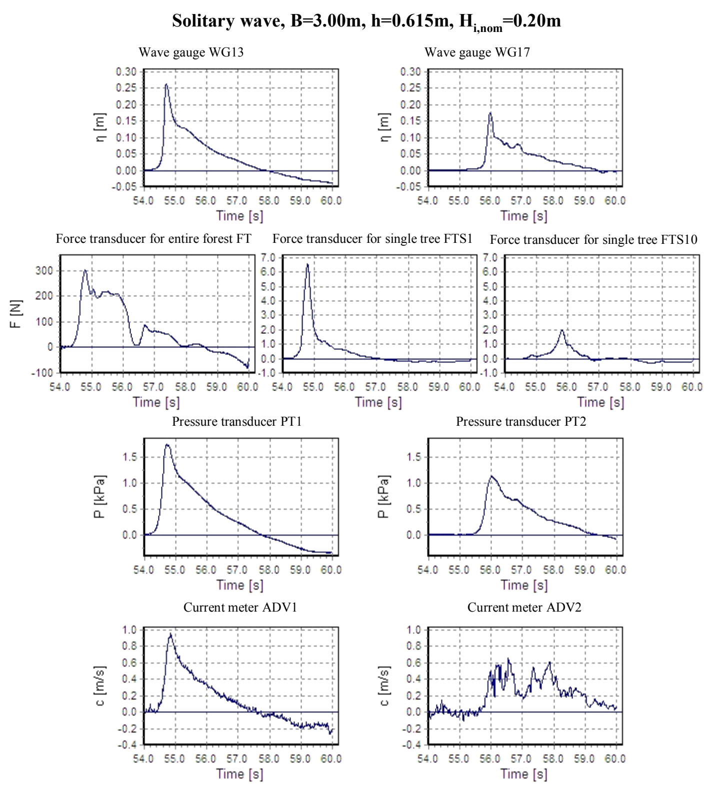

Figure 7. Exemplary signals from measuring devices (see Fig. 4 for the device location)

Due to the requirement of the measurements of the forces exerted by waves on the entire forest, the horizontal part of the beach platform in the 2m wide flume was constructed as a system which is moveable in the direction of wave propagation. The system consisted of a moveable steel frame connected to the force transducer FT at top of which two plywood plates with the force transducers for a single tree model were placed (see Figs. 5 and 6a). More details on the development of the measuring instrumentation and the experimental set-up can be found in Oumeraci et al. (2009a and b).

Solitary waves of varying incident wave height $H_{i,nom}$=0.04-0.20m were employed to represent a tsunami. The applicability of the forest to damp storm waves was also investigated by generating both regular and irregular waves (JONSWAP spectrum) of different incident wave periods $T_{i,nom}(T_{pi,nom})$=0.7-2.5s and incident wave heights $H_{i,nom}(H_{si,nom})$=0.04-0.20m (of wave steepness $0.02<H/L<0.06$). The total water depth was h=0.465-0.615m (see Fig. 6b).

3 Analysis of experimental data

The damping performance of the mangroves for solitary waves is shown exemplarily in Fig. 7 that includes signals from the measuring instrumentations placed in front of and at the end of the forest model. A significant reduction of wave height, forces, pressure and flow velocities can be observed in case of a wide forest (B=3.0m).

Determination of wave evolution modes

A classification of wave evolution modes observed during wave propagation in the 2m and the 1m wide flumes is essential for an efficient analysis of the experimental data and for the estimation of the effect of the forest on wave attenuation. The evolution modes are determined on the basis of the measured signals and video camera records by considering the following aspects: location of incipient wave breaking, generation of wave fission (in case of solitary waves) or generation of higher harmonics (in case of regular/irregular waves). These evolution modes are discussed exemplarily for solitary waves propagating in the 2m wide flume including the forest model (see Fig. 8); however the proposed classification is also applicable to the other wave types considered and to the wave propagation in the 1m wide flume (without the forest model):

- **Nonbreaking wave conditions**

- Propagation of nonbreaking incident wave with generation of soliton fission, termed evolution mode "EM1" (see Fig. 8a). The process of wave disintegration into a solitary wave train of decreasing heights (termed solitons) was induced by the water depth change from h=0.465m-0.615m in front of the beach to d_r=0.05-0.20m over the beach platform. This type of wave behaviour is typical for wave propagation over submerged obstacles and was reported e.g. by Madsen and Mei (1969). Evolution mode "EM1" was observed generally for the smallest incident wave heights: $H_{i,nom}$=0.04m for water depth h=0.515-0.615m and $H_{i,nom}$=0.08m for h=0.615m.

- **Breaking wave conditions**

- Propagation of broken waves over the beach slope (in Region 1) with generation of soliton fission, termed evolution mode "EM2" (see Fig. 8b). The incident wave breaks over the beach slope and propagates further as a turbulent bore. In some cases, generation of the wave fission could not be stated clearly, since the wave form became very complex after wave breaking and a longer travel distance would be required for a full development of this process. Evolution mode "EM2" occurred only for the smallest water depth h=0.465m, for relatively high waves $H_{i,nom}$=0.12-0.20m.

- Propagation of waves broken between the end of the beach slope and the beginning of the forest model, i.e. in front of the forest (in Region 2) with generation of soliton fission, termed evolution mode "EM3" (see Fig. 8c). Two sub-modes can be distinguished in this case: (i) generation of wave breaking first followed by wave disintegration into solitons (observed if the inception point of breaking event was very close to the end of the beach slope), (ii) generation of wave fission first followed by wave breaking and a further development of wave scattering (observed if the inception point of breaking event was close to the beginning of the forest). Similarly to "EM2", the appearance of the solitons at the rear part of the broken wave was difficult to determine due to the complex wave form. Evolution mode "EM3" was the most often observed pattern of all tests.

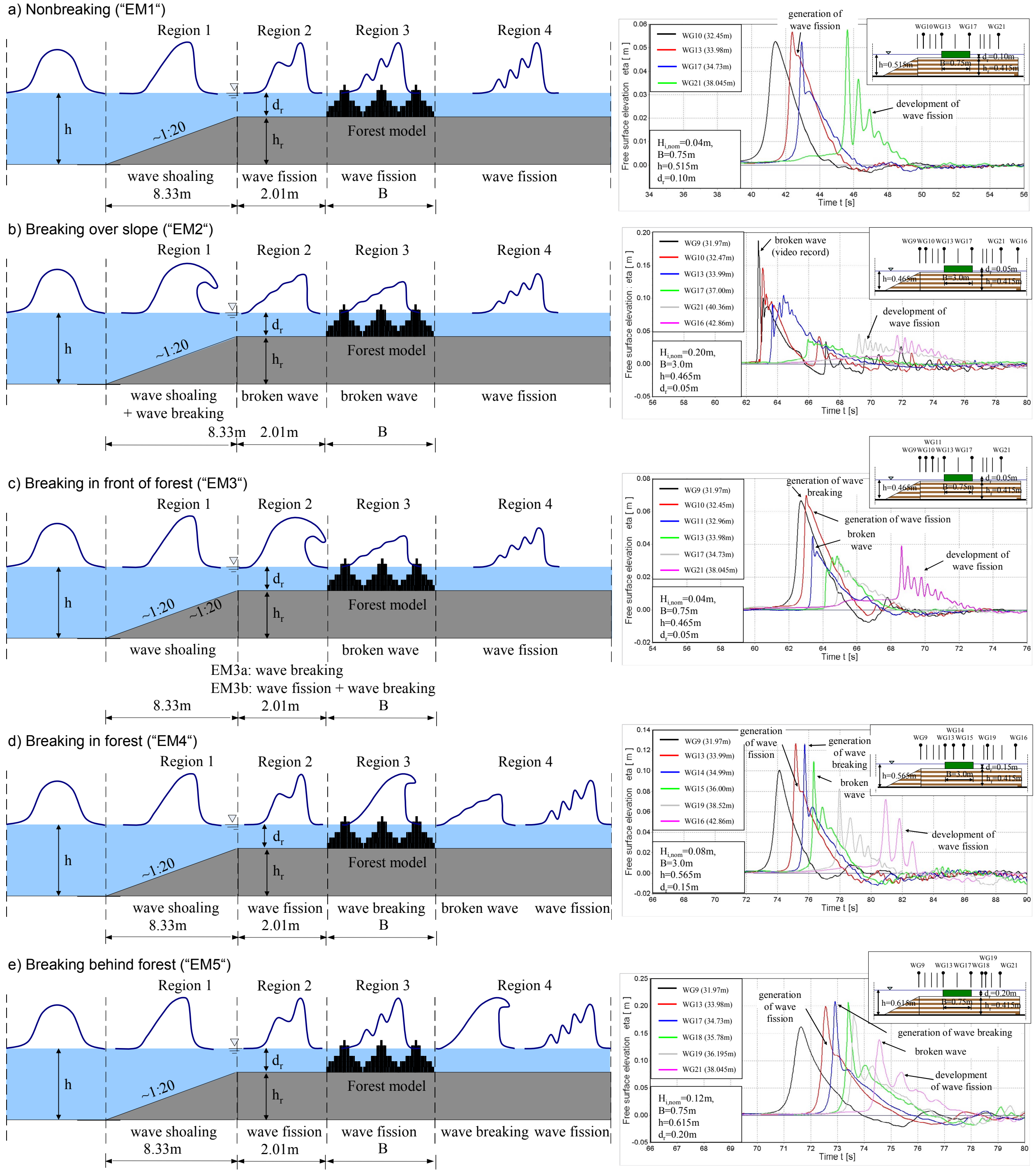

Figure 8. Solitary wave evolution modes observed in the 2m wide flume with the mangrove forest model

- Propagation of broken waves in the forest model (in Region 3) with generation of soliton fission, termed evolution mode "EM4" (see Fig. 8d). A single incident solitary wave starts to disintegrate into solitons already in front of the forest. Due to the amplification of the height of the leading soliton accompanying wave fission, the wave became unstable and broke within the forest. After the accomplishment of the breaking process, a further development of wave fission was observed. Evolution mode "EM4" occurred generally for forest widths B=1.50-3.0m, the highest water levels h=0.565 and 0.615m and for the wave height range $H_{i,nom}$=0.08-0.16m.

- Propagation of broken waves in the forest model (in Region 4) with generation of soliton fission, termed evolution mode "EM5" (see Fig. 8e). This type of wave evolution was observed solely for the smallest forest width B=0.75m, for h=0.565m and $H_{i,nom}$=0.08m as well as for h=0.615m and $H_{i,nom}$=0.12m. The characteristic of this mode is similar to that of the evolution mode "EM4".

On the basis of the analysis of the observed solitary wave evolution modes, the following conclusions can be made:

- Wave disintegration into at least two solitons (with the leading wave considered as the first soliton), followed by oscillatory waves was observed in all evolution modes.
- Wave breaking event did not suppress the generation of the fission process.
- Increase of water level resulted in a smaller number of the emerged solitons. On the other hand, the solitons number tends to increase with the increase of the incident wave height and the increase of the forest width.

Wave attenuation

The attenuation performance of the forest model as a reduction of the forces exerted on single trees along the forest is considered in the preliminary analysis. For this purpose, a comparative analysis of the signals from the force transducers for single trees (FTS1-FTS10) was performed for each tested forest width and water depth including the distinction among the incident wave heights and the observed evolution modes (see Figs 9a-c). The conclusions of this analysis are summarized below:

- For nonbreaking wave conditions (i.e. "EM1"), the effect of the forest width B on the solitary wave damping is negligible, even for the largest forest width B=3.0m. As shown in Fig. 9c, the maximum force measured at the beginning of the forest for $H_{i,nom}$=0.04m was about 0.36N and at the end of the forest about 0.33N (reduction by about 8%), while for $H_{i,nom}$=0.08m about 1.78N and 1.28N, respectively (reduction by about 28%).
- For wave breaking conditions (i.e. "EM2-5") the energy dissipation associated with the breaking process as well as the wave propagation distance should be additionally considered. Taking exemplary the case of the incident wave height $H_{i,nom}$=0.04m that exerted a load of approximately 1.5N at water depth h=0.415m, the force measured at the end of the forest was about 1.2N for B=0.75m (reduction by about 20%), while only about 0.2N for B=3.0m (reduction by about 87%) (see Figs. 9a and b). In the latter case, such a significant force reduction is primarily due to the longer wave travelling distance (thus larger energy dissipation due to breaking) and the presence of the forest. Measurements of the forces exerted by incident waves on the beach only (without the forest model) would be required to provide a complete damping characteristic of the mangroves.
- The increase of the total water depth h leads to changes in the wave evolution modes. For instance, wave of height $H_{i,nom}$=0.04m broke in front of the forest for h=0.465m ("EM3"), but it propagated without breaking ("EM1") for h=0.615m (see Figs. 9b and c). Higher reduction

of the forces is attributed to the lower water depths, which are more favourable for wave breaking generation (i.e. higher rate of wave energy dissipation due to the turbulent effects).
- A tendency to higher wave attenuation for larger incident wave heights can be observed (see Fig. 9b).

The transmission coefficient, expressed as a ratio of the maximum forces measured by the force transducers placed at the end and at the beginning of the forest, is shown in Fig. 9d. Generally, the maximum transmission of the wave forces occurs for nonbreaking wave conditions ("EM1") and reaches almost Kt=1.0.The minimum transmission (about Kt=0.14) of the wave forces is observed for the lowest total water depth h=0.465m with the most favourable conditions for wave breaking. There is a clear tendency for the force transmission coefficient to decrease with relative forest width B/L_i, For the broken waves ("EM2-5") this is caused by a higher rate of wave energy dissipation over a longer travelling distance through the forest.

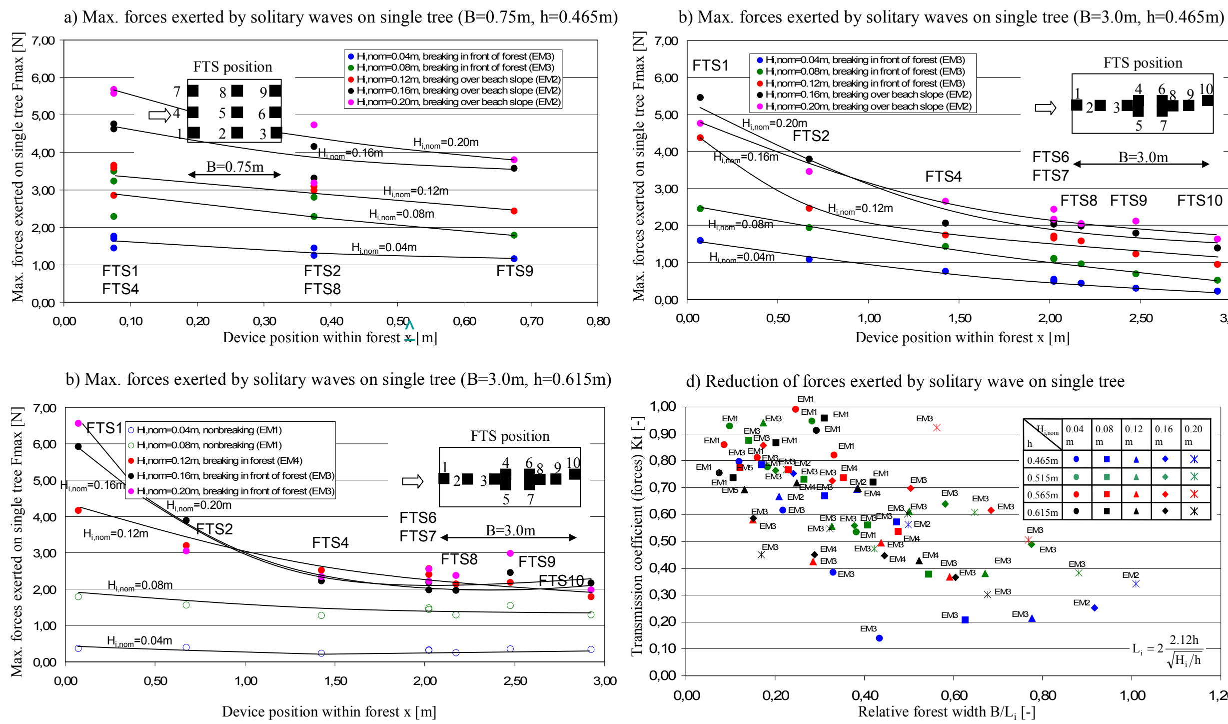

Figure 9. Damping performance of mangrove forest for solitary waves

Conclusions and outlook

The hydrodynamic performance of mangrove forest (*Rhizophora* sp.) under tsunami and storm wave conditions was investigated experimentally for varying forest widths, water depth and incident wave characteristics. The final design of the mangrove models resulted from the parameterization procedure based on the stiff assumption (with a root system and a trunk considered only). The properties of the parameterized models, specified by the field surveys and the concept of the submerged root volume ratio, were determined from the experiments under steady flow conditions. The forest damping characteristics for solitary waves was determined by the reduction of the forces exerted on single trees. The role of the classified wave evolution modes (i.e. nonbreaking or breaking with different location of incipient breaking in relation to the forest model) was found to be important. In case of the nonbreaking waves, the forest width does not affect significantly the force reduction, even for the largest forest width B=3.0m. The importance of the forest width in case of the breaking waves cannot be determined explicitly, since energy dissipation due to breaking event accompanies wave propagation through the mangroves. The maximum force reduction (about Kt=0.14 – 0.20) was observed for waves breaking at the smallest water depth h=0.465m.

Future work will be focused on: (i) the development of the procedure allowing to determine solitary wave transmission, reflection and energy dissipation coefficients in case of generation of the fission phenomenon, (ii) determination of vegetation resistance coefficients using Morisson equation, (iii) numerical modelling of the forest damping characteristic. Tests using a bore to represent a tsunami propagating onshore are also planned.

Acknowledgments

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