HENRY
Hydraulic Engineering Repository

Ein Service der Bundesanstalt für Wasserbau

Article, Published Version

Chang, Che-Wie; Mori, Nobuhito

Engineering functional evaluation of mangrove forests for coastal disaster reduction

Hydrolink

Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/109462

Vorgeschlagene Zitierweise/Suggested citation:
Chang, Che-Wie; Mori, Nobuhito (2019): Engineering functional evaluation of mangrove forests for coastal disaster reduction. In: Hydrolink 2019/4. Madrid: International Association for Hydro-Environment Engineering and Research (IAHR). S. 110-113. http://iahr.oss-accelerate.aliyuncs.com/library/HydroLink/HydroLink2019_04_a9d9sas0das9f.pdf.

Standardnutzungsbedingungen/Terms of Use:

Die Dokumente in HENRY stehen unter der Creative Commons Lizenz CC BY 4.0, sofern keine abweichenden Nutzungsbedingungen getroffen wurden. Damit ist sowohl die kommerzielle Nutzung als auch das Teilen, die Weiterbearbeitung und Speicherung erlaubt. Das Verwenden und das Bearbeiten stehen unter der Bedingung der Namensnennung. Im Einzelfall kann eine restriktivere Lizenz gelten; dann gelten abweichend von den obigen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Documents in HENRY are made available under the Creative Commons License CC BY 4.0, if no other license is applicable. Under CC BY 4.0 commercial use and sharing, remixing, transforming, and building upon the material of the work is permitted. In some cases a different, more restrictive license may apply; if applicable the terms of the restrictive license will be binding.

ENGINEERING FUNCTIONAL EVALUATION OF MANGROVE FORESTS FOR COASTAL DISASTER REDUCTION

BY CHE-WEI CHANG & NOBUHITO MORI

Mangrove forests are widely considered as the major type of green infrastructures or Ecosystem-based solutions to Disaster Risk Reduction (Eco-DRR) in Southeast Asia, South Asia and the Pacific Islands. Historical records show clearly the capability of mangrove forests as a natural barrier, but their mechanism in reducing energy of tsunamis, storm surges and waves is still not well understood. Recent studies have contributed to progress in quantifying the engineering effects of mangrove forests against coastal hazards, and have identified future research needs.

Introduction

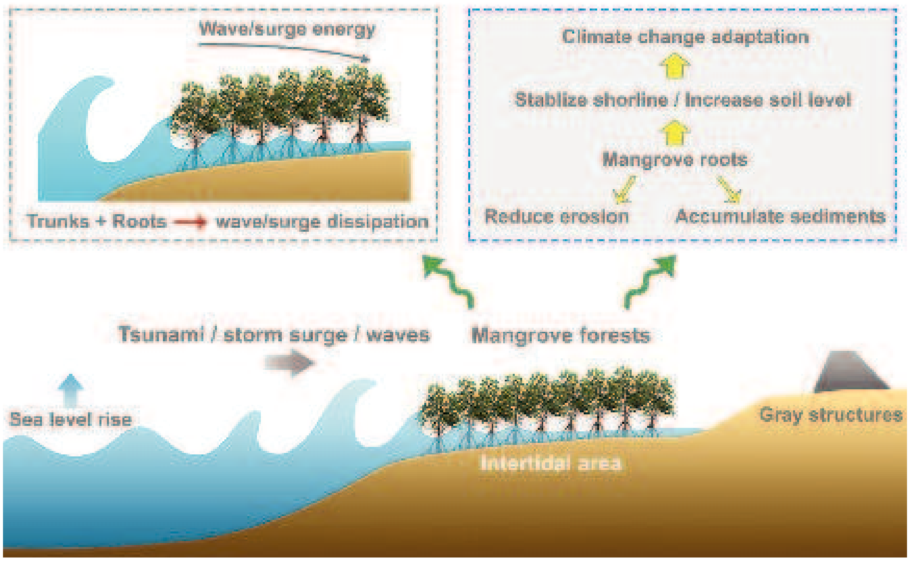
Green infrastructure, or Ecosystem-based Disaster Risk Reduction (Eco-DRR) has become popular after the *Sendai Framework for Disaster Risk Reduction 2015-2030*[1]. Likewise, the *Intergovernmental Panel on Climate Change Fifth Assessment Report*[2] pointed out the importance of green infrastructure for coastal flooding mitigation. The cost efficiency of this approach and its capability of adapting to the changing climate have drawn a lot of attentions around the world[3], [4].

The green infrastructures that function as natural protective barriers for coastal hazards mainly include coastal dunes, sandy beaches, coastal forests, mangroves, coral reefs and salt marshes. Dunes and sandy beaches are popular due to their ease of maintenance by nourishment or restoration. Coastal forests and mangroves are widely recognized for their protective function through wave or hydrodynamic energy reduction, e.g. storm waves, surges and tsunamis. Coral reefs and salt marshes are also capable of attenuating wave energy, but they are both difficult to install or maintain.

Coastal pine trees have been used in East Asia for coastal protection for decades. As reported after the 2011 Tohoku Earthquake Tsunami[5], coastal pine forests played a critical role in reducing the tsunami energy and in trapping debris. Their engineering function has also been well studied due to the simple structure of their trunks and branches. Another major coastal tree species, mangroves have been identified as natural buffers in tropics and subtropics since the 2004 Indian Ocean

Figure 1. Planted mangrove afforestation in South Tarawa, Kiribati

Figure 2. Protective/Eco-DRR function of mangroves against coastal waves and climate change



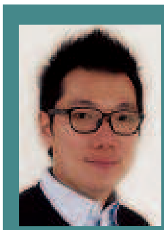
Earthquake Tsunami[6], [7]. Additionally, with large capacity for carbon storage, mangroves are valuable to climate change mitigation. In fact, the plantation of mangroves is becoming prioritized in Southeast Asia and the Pacific Islands to combat extreme disasters and mitigate the effects of climate change. Figure 1 shows a planted mangrove afforestation in South Tarawa, Kiribati. Furthermore, by dissipating the energy of incoming waves/flows, mangroves can stabilize shorelines by reducing erosion and accumulating sediments, which can counteract sea level rise. A sketch of the protective function of mangroves against coastal waves and climate change is in Figure 2.

Current scientific studies of these aspects of coastal protection are relatively limited. Because the structural complexity, physical properties and botanical characteristics of mangroves are not sufficiently addressed, the engineering function of mangrove forests for coastal protection has not been well investigated and requires further study. In the following, some of the representative works on mangroves and coastal vegetation for Eco-DRR are reviewed. The unsolved challenges and potential future research directions are also presented.

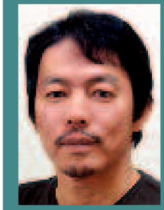
A lesson from nature

In the 2004 Indian Ocean tsunami, reduced mortality and loss of property were observed in regions with dense mangrove forests, unveiling the potential of mangroves as protective infrastructure against extreme coastal disasters. Similar findings after Typhoon Haiyan in 2013 further proved the buffering function of mangroves. In the aftermath of these events, abundant field studies identified the effects of mangroves on disaster mitigation, and therefore drew increasing attention from both the public and researchers.

Some of the very first reports after the Indian Ocean Earthquake Tsunami pointed out the critical role of coastal vegetation in reducing tsunami damage[6]. According to these reports, the villages behind mangrove forests experienced less damage than other regions without natural barriers. Kathiresan and Rajendran[8] conducted a field survey in several coastal hamlets along the southeastern coast of India and suggested planting mangroves and other species for future tsunami hazard protection. Similarly, a field survey along the coast of Sri Lanka and Thailand showed that mangrove-type vegetation was one of the most effective species in tsunami wave dissipation due to their complex root structures[7]. The role of mangroves in reducing tsunami damage has also been identified in other tsunami events, e.g. the Indonesia Sulawesi Earthquake Tsunami[9].



Che-Wei Chang is currently a Specially Appointed Assistant Professor at Disaster Prevention Research Institute (DPRI) of Kyoto University. He accomplished his PhD at Cornell University. His research interests include coastal disaster mitigation, ecosystem-based disaster risk reduction (Eco-DRR) and nearshore hydrodynamics. He has abundant experiences in vegetation-related research using theoretical, numerical and physical modeling.



Nobuhito Mori is a Professor at Disaster Prevention Research Institute (DPRI) of Kyoto University. He has extensive experience in climate change impacts on coastal hazards and risk assessment of coastal disasters. He leads Japanese nationwide research projects on climate change impact on coastal hazards funded by MEXT of Japan since 2012.

The effects of mangroves on reducing storm waves and surges were relatively well recognized in the past. Das and Vincent[10] presented a correlation of mangrove shields with the reduction of deaths during a super cyclone in 1999. More recently, several villages were saved by mangrove shields during the super typhoon Haiyan in 2013 while the destruction of mangroves also triggered a heated discussion on the effectiveness of different mangrove species, the assessment of mangrove forests recovery and future planting of mangroves[11].

Despite general agreement in their capability of reducing wave energy, the effectiveness of mangrove forests during extreme events like tsunamis or storm surges is still unclear quantitatively. As it is unlikely that they can stop the destructive power of extreme waves, “what is the protection level that mangrove forests can provide?” becomes a must-answer question to scientists.

Scientific research progress

Historical events and field studies demonstrated the protective function of mangrove forests against extreme tsunamis, storm waves and storm surges. An improved understanding of wave-mangroves interaction will benefit coastal protection design and management. To better quantify the effectiveness of mangrove forests, enormous efforts have been made via numerical and physical modeling to address different aspects of the issue, e.g. physical processes in wave-vegetation interactions and wave attenuation by vegetation. Some of the representative studies and research progress are discussed next.

Numerical modeling

Numerical or mathematical modeling has long been conducted to study the interaction between waves and vegetation since the 1980s. In the early stage of this work, several macro-scale models were introduced, which used an additional drag term to account for the dissipation by vegetation[12], [13], [14]. These pioneering studies provided a conceptual methodology to address vegetation effects, while the prescription of wave profiles and the calibration of empirical coefficients restrained their application. Detailed flow fields were not available using these models.

With growing requests for a better understanding of vegetation-induced dissipation, another type of numerical models based on the Navier-Stokes (N-S) equations were developed in recent years. These models simulate the flow in detail using appropriate numerical approaches and turbulence closure schemes. By resolving each individual tree in numerical discretization, N-S models detail the flow features and turbulent interactions among vegetation, providing more insight into the energy dissipation process. Representative studies of this type can be found in the work of several investigators[15], [16], who developed models based on the Reynolds-averaged Navier-Stokes (RANS) equations. In addition, Large eddy simulation (LES), another type of N-S models, has also been applied to study flow/wave-cylinder interaction problems, where detailed information of wave forces on cylinder arrays can be obtained[17]. Despite detailed flow fields and physical mechanisms provided in these direct numerical approaches, both RANS and LES models demand considerable computational resources for a large forest region including complex tree shapes, which may limit their engineering application.

Another type of intermediate semi-analytical model was developed recently based on the multi-scale homogenization theory in which the linearized RANS equations were applied[18]. This model was later extended numerically to three-dimensional problems for multiple forest patches of arbitrary shapes[19], [20]. This type of models simulates micro-scale flow motions surrounding trees which are then used to solve macro-scale wave dynamics. However, the use of linearized governing equations and the requirements of simplified vegetation conditions limit the application of this model in mangrove environments.

Depth-integrated wave models, based on nonlinear shallow water equations or Boussinesq-type equations, have become popular due to the balance between physical approximations and computational efficiency, which makes possible their application to larger areas. Similar to the macro-scale approach, the vegetation effects are modeled as an additional dissipation term in the momentum equations, which relies on precise prescription or calibration of empirical coefficients. In some of these models[21], [22], the vegetation effects were integrated as enhanced bottom friction which cannot well represent vegetation-induced resistances. On the other hand, the Morison-type formula[23] has been considered more appropriate for parameterizing vegetation effects and has been widely used[24]. In addition to depth-integrated models, a nearshore spectral wave model has been developed[25] by employing a layer approach to account for vertical variation for mangrove-type vegetation. Similarly, calibrations of certain empirical coefficients were required.

Despite the remarkable progress of computational models, it should be noted that simplified vegetation conditions have been mostly applied in these models. The structural complexity of mangrove trees has not been well addressed and needs to be taken into account in future model development.

Physical modeling

In addition to the development of numerical tools, physical tests have been conducted for years to better assess the energy dissipation capacity of vegetation and complement numerical simulations in accounting for different interaction processes. Using simplified tree models, such as uniformly-distributed cylinders, wave propagation through coastal forests were investigated in some studies[21], [26]. Similarly, vertical cylinders were used to study the impact of an open gap in coastal forests on tsunami runup[27]. These simplified tree models have been well applied to study coastal trees without complicated structures, e.g. pine trees.

On the other hand, as a particular feature of mangroves, their complex root system has been widely considered effective in reducing wave energy. Simplified tree models may underestimate mangrove effects on wave attenuation and limit their application to mangrove environments without considering the effects of the root system. Thus, in the past decade, several studies started to address the complex structures of mangroves using artificial tree models. Some investigators proposed a parameterized tree model[28], which consisted of a group of cylinders with different heights, to represent prop roots on the basis of identical hydraulic resistance. In these studies, mangroves were represented by simplified structures based on certain equivalent physical characteristics of tree models and prototype mangroves. Thereafter, several studies made an improvement by reconstructing artificial mangrove models with prop roots based on field measurements[29], [30].

All the physical models discussed above proved the importance of vegetation on reducing wave energy. The different experimental findings in simplified tree models and artificial mangrove models necessitated the inclusion of the prop roots in both numerical and physical modeling. The recent artificial mangrove model studies greatly improved the understanding of the root system in dissipation processes. The roots can reduce flow speed, increase friction, and enhance wave dissipation by means of turbulent interactions. The vertical variation of porosity due to the root system enables mangroves to have higher potential for wave attenuation.

Figure 3. The 3D image of a mangrove

Until today, however, there is still a lack of a consensus on the effectiveness of mangrove forests on disaster mitigation, quantitatively. Field studies have demonstrated the complexity of mangrove structures and their large regional variation depending on the environments, which cannot be represented by the artificial/idealized tree models. Therefore, a proper representation of realistic mangrove characteristics should be a priority in future modeling.

Recent advances in laboratory experiments

Wave force measurements

As mentioned above, the Morison-type formula has been widely applied to simulate wave forces and parameterize vegetation-induced dissipation in most macro-scale or depth-integrated numerical models. Calibration is usually required to determine the force (drag and inertia) coefficients based on wave amplitude measurements in laboratory experiments. Thus, the determination of force coefficients and the resulting wave dissipation depends on the accuracy and reliability of experimental data. The proposed drag/inertia formulas became unique for each study and cannot be generalized. On the other hand, direct measurements of wave forces on tree models were applied to several recent studies, in which the force coefficients were computed by the Morison-type equation with the measured velocity and forces[31], [32]. Without calibrations of force coefficients with wave measurements, their proposed formulas in terms of flow parameters (Reynolds /Keulegan-Carpenter numbers) are applicable to a certain range of wave/flow conditions.

A new 3D real tree model

As presented in field studies, real mangrove structures are more complicated than artificial/idealized tree models. A recent step forward is a set of model-scale experiments using 3D-printed mangrove models[32]. Based on 3D scanned images from the field, the detailed structure of prop roots was scaled down and was reproduced at a scale of 1/7 as shown in Figure 3. Wave-induced forces on tree models were directly measured such that the force coefficients in the Morison-type formula were obtained based on the experimental data. Comparing with previous work using rigid cylinders with the same trunk diameter[31], it was observed that force coefficients become more scattered but within the same range due to the impacts of prop roots. The fluctuating velocity profiles, which were different from those

A mangrove forest on the edge of a remote island in Raja Ampat, Indonesia (gettyimages)

in cylinder experiments, also indicated the non-negligible effects of prop roots, which should be taken into account for more precise parameterization of mangrove effects in numerical models. Such 3D scanned tree data can be used potentially in the direct numerical approach as well. Another set of laboratory experiments was also conducted by using real trees, which allowed further investigation of the flexibility and breaking conditions of real mangroves. Some of the experimental analyses are ongoing and will be discussed in future publications.

Conclusions and future directions

Mangrove forests, as one of the most well-known Eco-DRR in the tropics and subtropics, have been seen as one option against coastal hazards and climate change in the near future. To maximize the potential of mangroves in coastal protection, better quantification of the effectiveness of mangrove forests will be required. The first priority of the future studies should well address the incorporation of complex mangrove structures in both numerical and physical modeling. A latest technology, 3D laser scanner, can be useful to capture the detailed structures of mangrove roots in fields, which make it possible to rebuild more realistic tree models in laboratory experiments. The anticipated advantages include a precise determination of parameters based on experimental findings, which will be desirable for depth-integrated models. The scanned data can also be used in numerical computations to resolve detailed flow fields by using RANS/LES model. Furthermore, a comprehensive dataset, combing botanical and physical characteristics of mangroves such as age, size, root structure and rate of growth, will be required for integrated assessment of afforestation. This will make a breakthrough in quantitative evaluation of mangrove effects against extreme waves (short-term) and climate change (long-term). ■

References

[1] UNISDR (United Nations International Strategy for Disaster Reduction), 2015. Sendai framework for disaster risk reduction 2015-2030.
[2] Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report – Working Group II, 2014. Climate change 2014: Impacts, adaptation, and vulnerability.
[3] Sutton-Grier, A. E., Wowk, K. and Bamford, H., 2015. Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. Environmental Science & Policy, 51, 137-148.
[4] Reguero, B. G., Beck, M. W., Bresch, D. N., Calil, J. and Meliane, I., 2018. Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. PLOS ONE, 13, 1-24.
[5] Tanaka, N., 2012. Effectiveness and limitations of coastal forest in large tsunami: conditions of Japanese pine trees on coastal sand dunes in tsunami caused by Great East Japan Earthquake. Journal of Japan Society of Civil Engineers, Ser. B1, 68, II_7-II_15.
[6] Danielsen, F., Sorensen, M. K., Olwig, M. F., Selvam, V., Parish, F., Burgess, N. D., Hiraishi, T., Karunagaran, V. M., Rasmussen, M. S., Hansen, L. B., Quarto, A. and Suryadiputra, N., 2005. The Asian Tsunami: A Protective Role for Coastal Vegetation. Science, 310, 643.
[7] Tanaka, N., Sasaki, Y., Mowjood, M. I. M., Jinadasa, K. B. S. N. and Homchuen, S., 2007. Coastal vegetation structures and their functions in tsunami protection: experience of the recent Indian Ocean tsunami. Landscape and Ecological Engineering, 3, 33-45.
[8] Kathiresan, K. and Rajendran, N., 2005. Coastal mangrove forests mitigated tsunami, Estuarine, Coastal and Shelf Science, 65, 601-606.
[9] Goda, K., Mori, N., Yasuda, T., Prasetyo, A., Muhammad, A., Tsujio, D., 2019. Cascading geological hazards and risks of the 2018 Sulawesi Indonesia Earthquake and sensitivity analysis of tsunami inundation simulations, Frontiers in Earth Science, 7, 261.
[10] Das, S. and Vincent, J. R., 2009. Mangroves protected villages and reduced death toll during Indian super cyclone, PNAS, 106, 7357-7360.
[11] Villamayor, B. M. R., Rollon, R. N., Samson, M. S., Albano, G. M. G. and Primavera, J. H., 2016. Impact of Haiyan on Philippine mangroves: Implications to the fate of the widespread monospecific Rhizophora plantations against strong typhoons. Ocean & Coastal Management, 132, 1-14.
[12] Dalrymple, R. A., Kirby, J. T. and Hwang, P. A., 1984. Wave Diffraction Due to Areas of Energy Dissipation. Journal of Waterway, Port, Coastal, and Ocean Engineering, 110, 67-79.
[13] Mendez, F. J., Losada, I. J. and Losada, M. A., 1999. Hydrodynamics induced by wind waves in a vegetation field. Journal of Geophysical Research, 104, 18383-18396.
[14] Massel, S. R., Furukawa, K., and Brinkman, R. M., 1999. Surface wave propagation in mangrove forests. Fluid Dynamics Research, 24, 219-249.
[15] Marsooli, R. and Wu, W., 2014. Numerical investigation of wave attenuation by vegetation using a 3D RANS model. Advances in Water Resources, 74, 245-257.
[16] Maza, M., Lara, J. L., and Losada, I. J., 2015. Tsunami wave interaction with mangrove forests: A 3-d numerical approach. Coastal Engineering, 98, 33-54.
[17] Chakrabarti, A., Chen, Q., Smith, H. D., and Liu, D., 2016. Large eddy simulation of unidirectional and wave flows through vegetation. Journal of Engineering Mechanics, 142, 04016048.
[18] Liu, P. L.-F., Chang, C.-W., Mei, C. C., Lomonaco, P., Martin, F. L., and Maza, M., 2015. Periodic water waves through an aquatic forest. Coastal Engineering, 96, 100-117.
[19] Chang, C.-W., Liu, P. L.-F., Mei, C. C., and Maza, M., 2017. Periodic water waves through a heterogeneous coastal forest of arbitrary shape. Coastal Engineering, 122, 141-157.
[20] Chang, C.-W., Liu, P. L.-F., Mei, C. C., and Maza, M., 2017. Modeling transient long waves propagating through a heterogeneous coastal forest of arbitrary shape. Coastal Engineering, 122, 124-140.
[21] Augustin, L. N., Irish, J. L., and Lynett, P., 2009. Laboratory and numerical studies of wave damping by emergent and near-emergent wetland vegetation. Coastal Engineering, 56, 332-340.
[22] Yang, Y., Irish, J. L., and Socolofsky, S. A., 2015. Numerical investigation of wave- induced flow in mound-channel wetland systems. Coastal Engineering, 102, 1-12.
[23] Morison, J. R., O'Brien, M. P., Johnson, J. W. and Schaaf, S. A., 1950. The force exerted by surface waves on piles, Journal of Petroleum Technology, 189, 149-154.
[24] Chakrabarti, A., Brandt, S.R., Chen, Q. and Shi, F., 2017. Boussinesq modeling of wave-induced hydrodynamics in coastal wetlands, Journal of Geophysical Research: Oceans, 122, 3861-3883.
[25] Suzuki, T., Marcel, Z., Bastiaan, B., Martijn, C. M. and Siddharth, N., 2012. Wave dissipation by vegetation with layer schematization in SWAN, Coastal Engineering, 59, 64-71.
[26] Huang, Z., Yao, Y., Sim, S. Y., and Yao, Y., 2011. Interaction of solitary waves with emergent, rigid vegetation. Ocean Engineering, 38, 1080-1088.
[27] Ba Thuy, N., Tanimoto, K., Tanaka, N., Harada, K., and Iimura, K., 2009. Effect of open gap in coastal forest on tsunami run-up – investigations by experiment and numerical simulation. Ocean Engineering, 36, 1258-1269.
[28] Husrin, S., Strusinska, A. and Oumeraci, H., 2012. Experimental study on tsunami attenuation by mangrove forest. Earth Planets Space, 64, 973-989.
[29] Zhang, X., Chua, V. P. and Cheong, H.-F., 2015. Hydrodynamics in mangrove prop roots and their physical properties. Journal of Hydro-environment Research, 9, 281-294.
[30] Maza, M., Lara, J. L. and Losada, I. J., 2019. Experimental analysis of wave attenuation and drag forces in a realistic fringe Rhizophora mangrove forest. Advances in Water Resources, 131, 103376.
[31] Hu, Z., Suzuki, T., Zitman, T., Uittewaal, W., and Stive, M., 2014. Laboratory study on wave dissipation by vegetation in combined current-wave flow. Coastal Engineering, 88, 131-142.
[32] Chang, C.-W., Mori, N., Tsuruta, N. and Suzuki, K., 2019. Estimation of wave force coefficients on mangrove models. Journal of Japan Society of Civil Engineers, Ser. B2, 75, I_1105-I_1110.