BANQUE MONDIALE

Detailed proposal

ROOT – A Nature Based Solution to mitigate coastal erosion and to support mangrove restoration

Thematic Challenge 1. Which type of infrastructure (green, grey, or a combination of both) could be put in place to manage the impact of port development and port management on sediment movements, which lead to unwanted coastal erosion?

08/2020

SEABOOST

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Introduction

Under the influence of climate change, coastal areas of West Africa gather major challenges for the future of local communities (one third of the region's population), the local economy (more than 50% of West Africa GDP comes from coastal areas) and the local environment. A study published by the Worldbank under the title "THE COST OF COASTAL ZONE DEGRADATION IN WEST AFRICA: BENIN, CÔTE D'IVOIRE, SENEGAL AND TOGO" shows that coastal erosion rates can reach several meters per year, in hotspots like Saloum (Senegal), Grand Lahou (Ivory Coast) or East Coast of Cotonou (Benin). More than 50% of these countries' coastlines face significant erosion dynamics that cause severe impacts : limited access to fishing areas for local communities, infrastructure damages, loss of arable lands, relocation of coastal populations, …

To tackle these crucial stakes, several projects have been led to build and increase coastal resilience. Most of them focus on traditional hydrodynamics and sediment approaches, in order to assess the key local trends and to deploy large infrastructures (dikes, breakwaters, …) to counter erosion processes. These techniques provide immediate protection, effective if properly sized, against both erosion and flooding. However, after years, experts and local stakeholders highlight the major changes that these works induce on wide scale hydrodynamics, with, sometimes, undesirable effects on areas downstream of the hydrosedimentary cell. In addition, these are heavy works requiring high labor, technical and financial resources. These features impede the deployment of this type of approach since they are difficult to implement everywhere and they require materials and equipments that are not readily available locally (calibrated blocks, work barges, etc.). Therefore these techniques are not easily transferable to local stakeholders who are neither able to get involved in the design and construction, nor in the management of the structure (monitoring, maintenance...). Finally, these "grey infrastructures" do not produce high ecosystem services, as their design does not target this purpose and a double functionality (technical and ecological). On the contrary, they generate adverse environmental impacts that are highlighted, in particular, by the destruction of shallow water habitat and the disruption of the ecological connectivity both parallel and perpendicular to the coastline. These structures are opaque, unchanging in time and offer limited structural complexity with homogeneous characteristics and no specific adaptations to the local ecological conditions (local species, local ecological functionalities…).

In light of these limits, the ecological restoration of buffer habitats such as mangroves can prove to be an efficient, productive and resilient approach to protect coastlines whilst supporting co-benefits for local populations. This approach however, requires a maturation period during which the habitats settle and grow into functional buffers, and its efficiency strongly rests on the long term performance of available restoration techniques.

Thus, regarding coastal ecosystem rehabilitation, several projects were conducted, with a special focus on mangroves in West African areas. These projects often rely on the rehabilitation of ecosystem engineers, which support both technical benefits (coastline protection), ecological functionalities and services. Moreover, these projects often involve local stakeholders, creating value, involvement and lowering local inequalities. Indeed, these projects require the mobilization of unqualified work forces and also allow the solicitation of low socio-professional classes that are relatively uninvolved in the everyday life of the community (women, former fishermen, ...).

Despite the existence of several rehabilitation projects, many uncertainties remain regarding restoration techniques, their performance, and the prerequisite conditions for efficient implementation. Success rates vary greatly between projects. For mangrove restoration programs for example, although they often lack long term monitoring, the available information shows that success and survival rates of transplanted seedlings are highly variable. Best projects reach around 50% survival rates; most of them reach 10-20% survival rates (*Primavera, J.H., Esteban, J.M.A. A review of mangrove rehabilitation in the Philippines: successes, failures and future prospects. Wetlands Ecol Manage 16, 345–358 (2008))* and some have a very high mortality rate, according to experts, even if long-term follow-up is poorly documented). These low survival rates are explained by poor project design, which itself can most often be explained by a misunderstanding of the local environmental conditions and hydrosedimentary processes that govern habitat distribution. . In the current state of knowledge, it is therefore very difficult to precisely define the contextual parameters governing the rehabilitation of such ecosystems, and thus to guarantee the success of restoration actions.

At Seaboost, (1) our analysis of West Africa's situation, (2) its comparison with other geographical areas, and (3) the consideration of the different approaches to tackle coastal erosion, led us to decide to merge traditional and ecological engineering to get the best of both. ROOT is one of the three Research and Development programs that the company has launched 4 years ago. It is based on a simple observation: the key factor of mangrove resilience and effective rehabilitation is the local hydrosedimentary conditions (considering of course that other external pressures such as pollution or wood harvesting are under control and kept to a level compatible with restoration)). Thus, we have designed a modular innovative object that reproduces the structure of a mangrove forest root system, using biomimicry, to perform similar effects on currents, wave attenuation and sediment transport. The solution aims for several goals :

1. **The structure of mangrove roots attenuates waves and currents whilst remaining permeable from a hydrological and ecological point of you: by reproducing these structural features, the ROOT system aims to affect local hydrodynamics with similar performances and permeability.**
2. **By copying mangrove effects on local abiotic conditions, the ROOT solution aims to create the appropriate conditions for spontaneous mangrove settlement and development, therefore maximizing growth and survival of young trees. Over time, these regenerated natural mangrove habitats take over.**
3. **By reproducing mangrove roots geometry, the ROOT solution aims to support part of the associated ecosystem services (fisheries, crabs and shells capture and culture, science, …) and to create new ones (activity for local communities, local empowerment, …)**
4. **The ROOT solution aims to rest on the deployment in shallow waters of modular and low tech structures. The objective is to make them as affordable as possible from a technological standpoint, as this will guarantee replicability in diverse and often complex work environments (material availability, production facilities, site accessibility, proximity of maritime works resources,…)**

1. ROOT: an innovative low tech approach

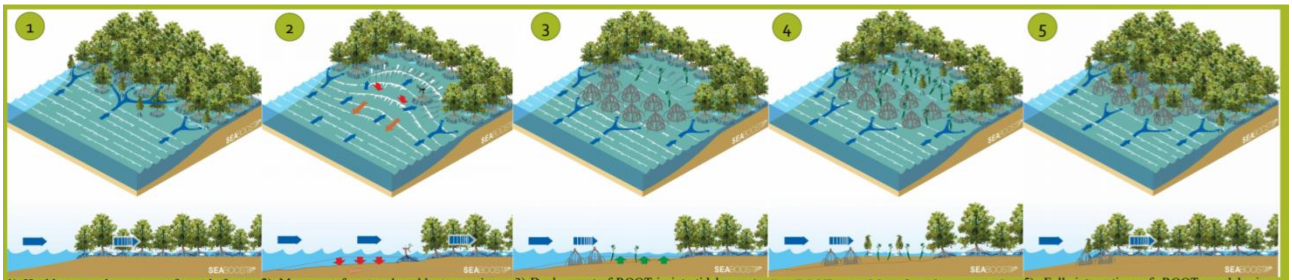
1.1 Technical innovation : a Nature Based Solution to fight erosion

ROOT is inspired by both traditional and ecological engineering. On one hand, the solution is based on the in-situ deployment of structures that can immediately generate effects on the physical environment as traditional engineering structure do. On the other hand, he acts likes engineering ecosystem by performing waves and currents attenuation with a porous system, sizeable, and supporting biodiversity settlement. It relies on a 2-steps approach:

- ROOT reproduces mangrove structural complexity to perform similar effects on its environment: waves and current attenuation, habitat, nursery, soils and stored carbon preservation, etc.

- ROOT creates a context allowing spontaneous mangrove rehabilitation, because it creates conditions similar to those precisely present in mangrove areas where propagules settle and grow.

Step by step, new mangrove trees will expand to finally recover the structure and replace it. A restored mangrove zone will thrive and carry all the associated ecosystem services.



1) Healthy natural mangrove forest before deforestation. 2) Mangrove forest vulnerable to erosion and strong wave action due to tree felling. 3) Deployment of ROOT in intertidal zone to restore hydrodynamics and sediment flow. 4) ROOT models fostering natural regeneration of mangrove trees 5) Full integration of ROOT models in restored mangrove forest.

Figure 1. Sequence of operation of the ROOT devices

ROOT system aims at reproducing mangrove structural complexity, to reach similar technical and ecological performances. “Structural complexity” means roots diameter and variability, roots tortuosity, roughness, anchoring depth, roots orientation, water column occupancy, etc. As it is not realistic to perfectly reproduce the whole natural structure, especially in a low tech approach, we performed more than 250 laboratory and numerical tests (in wave flume, in hexapod, SWAN, SWASH and homemade deterministic hydrodynamic model simulations) to assess key system parameters influence on system performance. It helped us to identify key properties (roots width, overall root density, roots roughness) and non essential ones (homogeneity of spatial distribution, anchoring depth, etc.). These tests helped us to define the main structures characteristics according to performance metrics (energy dissipation, reflection, drag coefficient,…), to feasibility constraints and in consistency with mangrove ecosystem

More than 8 designs were selected, and several workshops and interviews took place for months to correct, improve, merge, prioritize designs. This work involved more than 15 experts in each field of development, including mangrove ecology, functional ecology, hydrodynamics, sediments, structures sizing, numerical models, … One design was finally selected. 2 projects are on the run to:

- **Measure in situ ROOT performances to dissipate waves and flows in a pilot operation**
- **Measure at ½ scale ROOT performance in laboratory with prototypes. This will help us to build a a numerical tool that will simulate ROOT deployment on a site, in order to optimize deployment pattern.**

Most of these results are expected for 2022.

Please find hereunder our design at this stage. We have launched an action to file a patent on this technology. While we find it interesting to present our approach in this call, given the perspectives it opens up, it is also crucial for us to preserve the confidentiality of the information relating to the design, the materials, the mode of operation and deployment of this solution. In advance, please reserve the information transmitted here for the evaluation of the relevance of the proposed project within the strict framework of the call. Thank you in advance for your understanding on this subject.

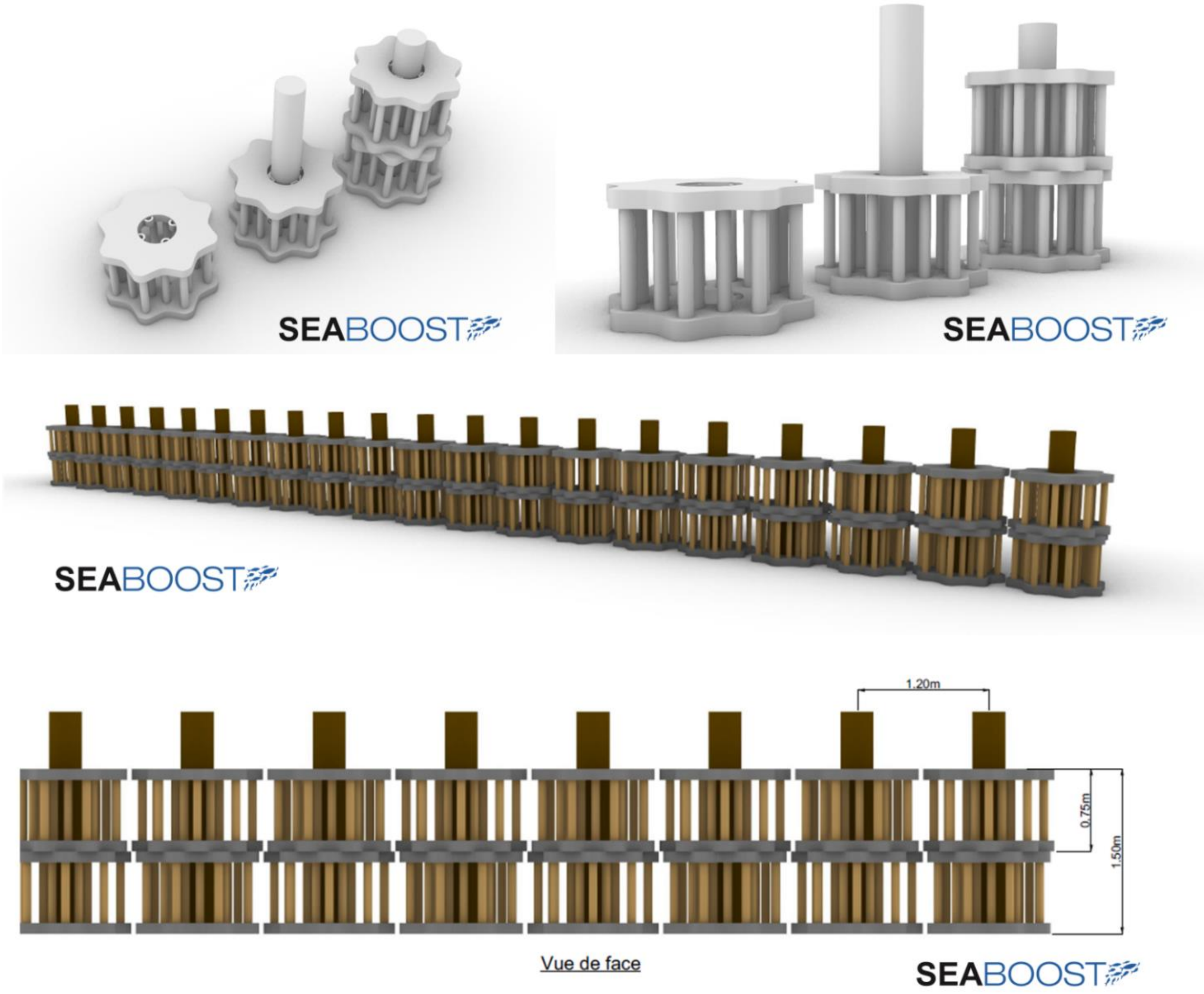


Figure 2. ROOT devices overview

ROOT object consists of 2 key elements:

- A central pile allowing the anchoring of the structures
- Stackable modules that reproduce the structural characteristics of a mangrove environment.

These structures are made up of wooden elements and cement parts (concrete that we have specially developed for applications in marine ecology or rudimentary mortars depending on the site). Most of material and production steps can be sourced on site, so that ROOT can enable local communities to gain skills and interest in the production, maintenance and deployment of that kind of structure. The structures are highly adaptable, since they can be modulated at any scale:

- at the scale of the whole structure (many piles and modules) according to the number of piles, their density, their spacing, their position, their number, ...
- at the scale of the pile, since the level of occupation of the water column can be dimensioned.
- at the module scale, since one can influence the thickness of the "roots" or their density, roughness, ... depending on the materials and treatments chosen.

Thus, we can adapt to the context from all perspectives: the needs in terms of performance, and the furniture, skills, resources available locally.

1.2 A highly versatile and replicable approach to fight against coastal erosion

Thanks to its great modularity, ROOT can be considered as an autonomous system or as a complementary approach to traditional works.

- On a natural site, not subject to past or current developments :
  - Deployment on a site previously occupied by the mangrove or conducive to its installation, to promote its installation through the creation of a favorable hydrodynamic context.
  - Isolated deployment on a hydrodynamically constrained site, to fight against coastal erosion and strong morphodynamic evolutions by dissipation of incidental energies, without necessarily targeting mangrove settlement
  - Joint deployment of ROOTs and a replantation action, to promote the growth and survival of replanted seedlings, diversify the area by spontaneous resettlement of additional individuals and reduce as much as possible the delay for the furniture of mangrove ecosystem services and not only ROOT's ones (wood production, tourism, ...).
- Within the framework of a joint deployment with traditional infrastructures
  - Deployment of ROOT on areas where hydrodynamical pressure do not need opaque work (minimal submersion risk for instance) to substitute ROOT to part of the grey infrastructure. We can evocate for instance an estuarine configuration, with needed dikes in front of the bay, and possible ROOT deployment inside the estuary to mitigate longshore erosion processes
  - Use ROOTs in areas adjacent to traditional infrastructure to limit the diffraction/reflection effects of gray structures, and generate complementary ecosystem services.
- Near an existing infrastructure
  - Provide a local complementary solution to bring additional performance to an aging structure or one that is not adapted to a context that has evolved.
  - Deployment of ROOT to mitigate large infrastructures impacts on hydrodynamics and sediments movements at wide scale on coastline, to limit for instance sediment losses downstream of a harbor facilities

1.3 What about ROOT performance?

ROOT conception relies on numerous tests, with many physical (wave flume, hexapod) and numerical (SWAN, SWASH, …) tools. These tests provided several results that lead us to two main conclusions:

- the idea of a structure reproducing the mangrove root intertwining is relevant in terms of wave and current attenuation performance
- and we are able to define some of these geometrical properties to maximize the ratio occupation/expected results of the structure.

For instance, we note that:

- Energy dissipation increases as root diameter decreases, and we reach an optima between 6 and 10 cm diameter in terms of performance versus feasibility (material availability, cost and transformation)

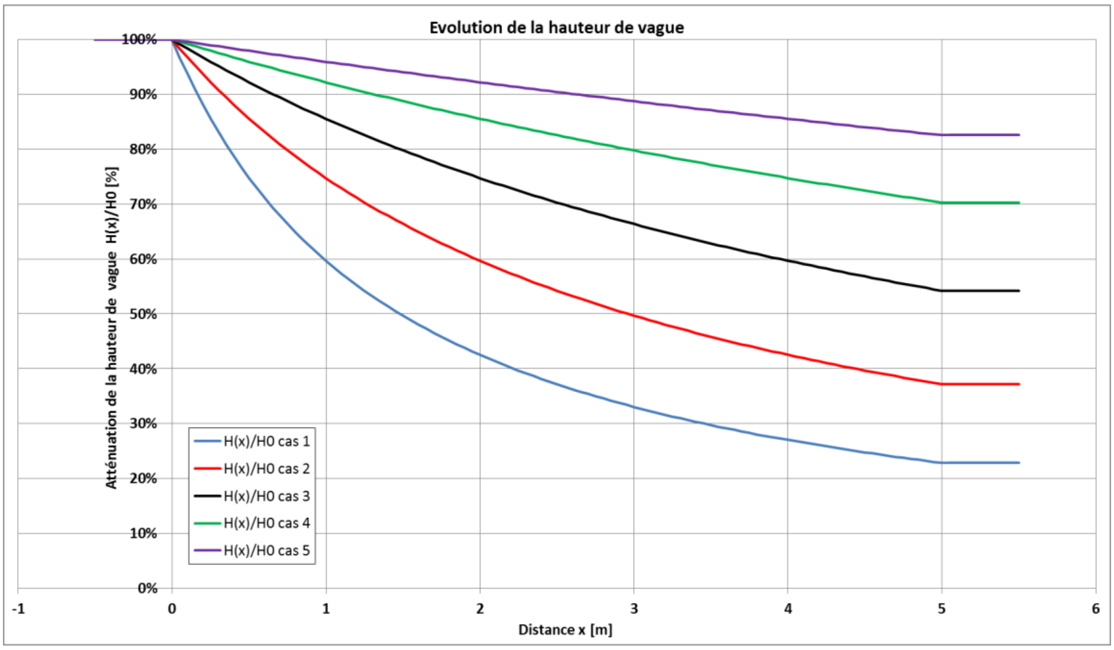


Figure 3. Results from physical and numerical models illustrating the evolution of energy dissipation as a function of the root diameter of the modules, at constant structure porosity.

- Dissipation increases as porosity decreases, but reflection also increases. Progressive porosity with discontinuous deployment pattern allows to meet both dissipation maximization and reflection minimization
- Roots millimetric roughness doubles energy dissipation versus smooth obstacles. Roughness also increases when we increase structure tortuosity, all other parameter fixed.

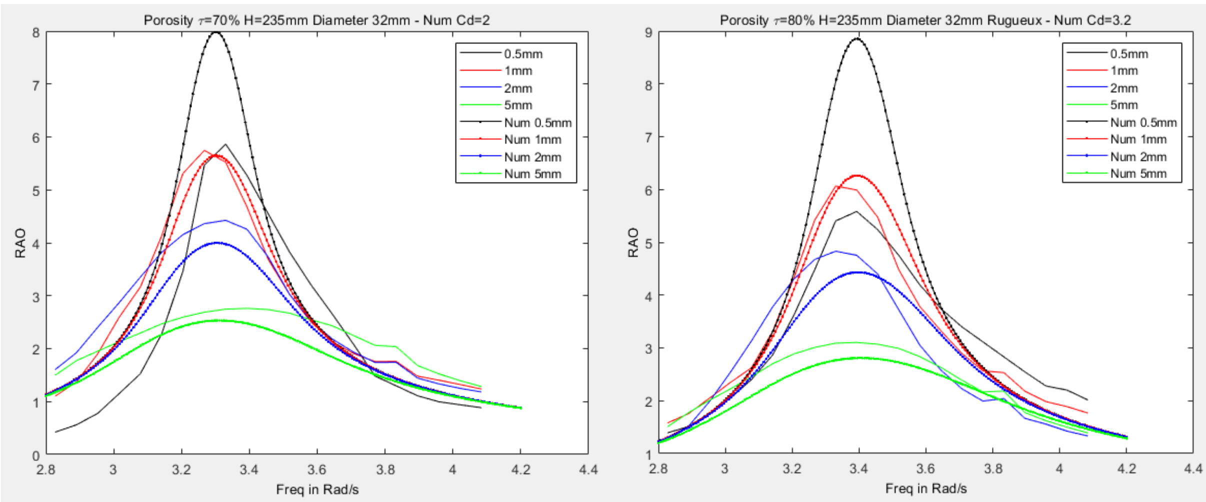


Figure 4. Evaluation of the effects of root roughness on energy dissipation performance (through the Cd dissipation coefficient measurement)

- Between 60 and 80 % of the dissipation occurs in the first 10 meters, according to the selected patterns. It means that we can reach a technical and economic optimum with a maximum 10 meters wide structure.

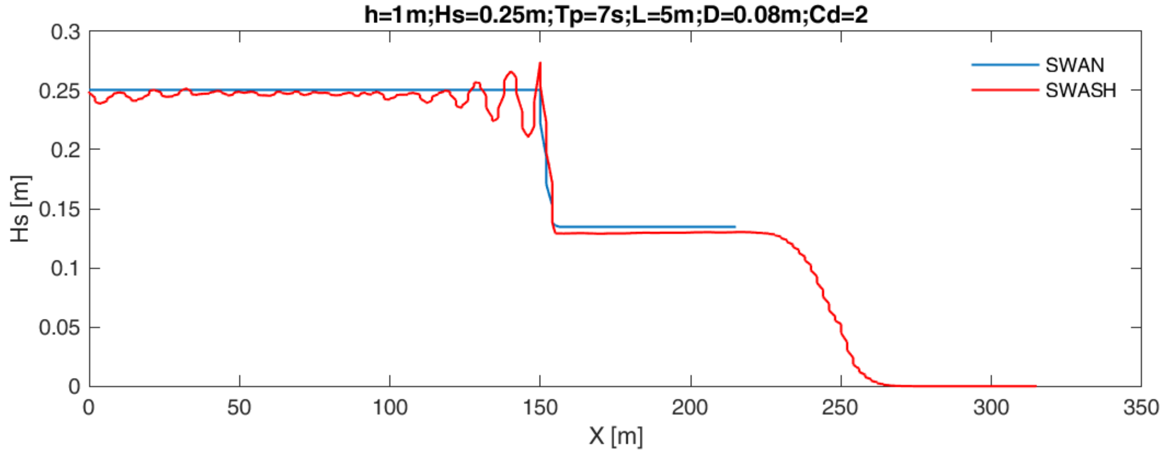


Figure 5. Representation in numerical model (SWASH & SWAN) of the attenuation of the wave height generated by the ROOT structure positioned in X = 150m

- Water column occupancy is key to dissipate wave energy, but the occupancy of the lower areas is more relevant for current dissipation as it helps to elevate the boundary layer.

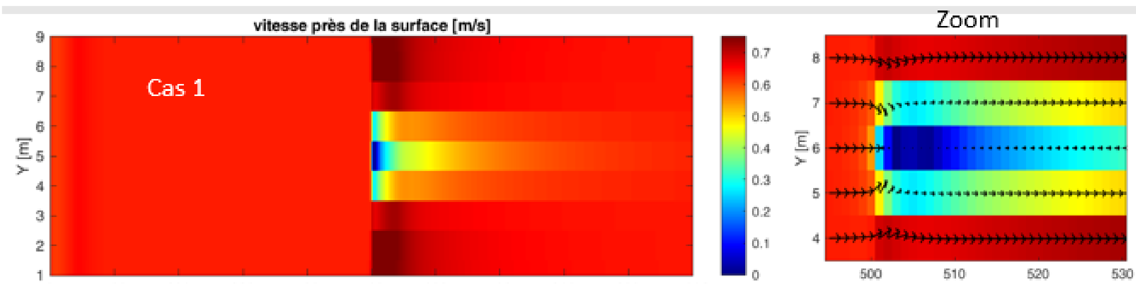


Figure 6. Analysis of energy dissipation levels as a function of the vertical variation of the porosity of the structure (heterogeneous, or homogeneous)

- The higher the obstacle is, the more it reflects the energy of the waves. There are optimized wave energy dissipation according to the spacing between the modules.

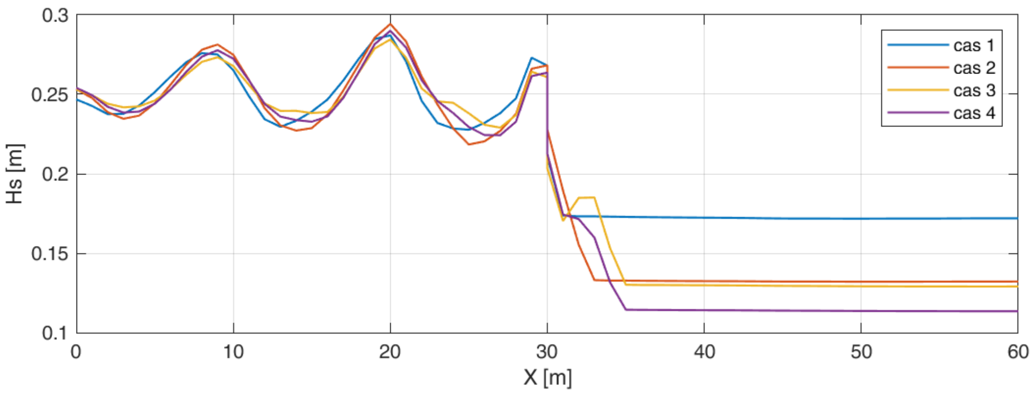


Figure 7. Figure illustrating the expected levels of energy dissipation according to different scenarios (one or 2 consecutive structures, with different spacing between structures).

- The spacings between modules tested (2 and 4 m) do not show significant difference in current velocity beyond about 30 m behind the modules, however, the velocity profiles and slowdown/acceleration zones are variable. These elements constitute subjects to be studied in depth in order to better understand the transport of propagules and sediments through the structure.

1.4 Create value to generate local involvement, empowerment and resources

The ROOT concept relies on technological accessibility and replication of the approach. For this, the bias is the strong involvement of local actors, through an accessible and adaptable technology. Therefore, ROOT generates several co-benefits on the socio-economic level:

- Involvement of the local actors, and in particular mobilization of socio-professional strata little or badly mobilized by traditional activities, such as in some places women, or fishermen too old to go to sea.
- Increased skills in production, maintenance and management of the systems (exploitation, usage controls, management of samples, etc.) but also in all the activities of the sector based on the modules, such as the production and exploitation of bamboos, for example, or the packaging of the resources collected.
- The replicability and accessibility of the technology also opens the door at the regional level to the renewal of similar operations associated with the networking of local authorities, with all the associated benefits in terms of exchanges, pooling of operations, etc...

These expected benefits contribute to a rise in the local standard of living, to the empowerment of populations, and thus to the sustainability of local communities through the sustainability of their territory. Furthermore, ROOT can help carbon capture, and limit carbon losses with mangrove soils erosion. This carbon can give birth to a valorization mechanism that can support part or the whole costs for structure running management

2. Prefeasibility analysis: technical, economics and ecological key figures

2.1 Technical feasibility : ROOT was built to maximize technical feasibility “everywhere”

A first feasibility analysis of the ROOT solution has already been done, and is based on several key analysis:

- <u>Is it possible to restore local hydrodynamical and sediment context with a ROOT-like solution?</u>
  - ⇨ *Laboratory tests and numerical modeling have demonstrated the relevance of a solution inspired by the mangrove root networks to dissipate the incidental energy of swells and currents, thus reducing the hydrodynamic forcing applied to the coast, and thus mitigating the erosive processes at work (cf 1.3. What about ROOT performance?)*
- <u>Is it possible to size appropriate ROOT structure dimensions for in situ application?</u>
  - ⇨ *In addition, the current prototyping phase (to be completed in 2022) will enable ROOT prototypes to be exposed at scale 1 to different swell and current conditions in order to precisely evaluate its performance and transfer it to a coastal hydrosedimentary model, in order to create a simulation module, applicable to different sites, to define the best ROOT deployment patterns.*
- <u>How can ROOT be produced, according to local context ?</u>
  - ⇨ *ROOT is designed to be highly accessible technologically. In complex contexts, it can be implemented using rudimentary mortars, for example, and local woods. It is possible to "upgrade" in environments that are more permissive. The use of local materials exclusively could impact the sustainability of the modules, but this would be precisely on sites where coastal communities are highly dependent on marine resources as a source of protein and activity. Consequently, these are contexts where ROOT can bring the most of its value in terms of benefits / affordability ratio, so*

that it is easy to replace items as they are low tech, and as local should be willing to do that, because it is cheap and supports local value and services.

- How can ROOT be deployed without engines?
  - ⇨ *ROOT is versatile and sizeable. If the deployment is not realistic for a single person, the elements will be manuportable and transportable with light means (small fishing boats, carts, ...). The dimensioning of the piles allows them to be anchored by hand (a technique notably used in Southeast Asia), and the assembly method allows either to install the modules on piles, or to install the modules first (depending on the tidal regime).*
- How to perform ROOT maintenance?
  - ⇨ *On sites with easy access to means of production and construction site, it is possible to design ROOT (materials, assemblies, anchors ...) to have no long-term maintenance, unless extreme events occur. On sites with limited resources, ROOT is based on local involvement and the increased skills of the players present to operate and manage the site. Consequently, the objective is to perpetuate some activities around the structure, and to organize a small system of management / maintenance / operation and conditioning of the resource, with the associated increase in skills.*

2.2 Economical feasibility : to make it affordable – keep it simple

As explained earlier in this document, ROOT is made of affordable material and simple production models. Thus, it is not easy to assess ROOT key metrics in terms of economics. Regarding its price per meter, it is depending on :

- **Local involvement**
- **Material nature and supply**
- **Production mode**

ROOT pricing depends on structure size and height, number of rows, production and deployment means, which are all depending on local context. We must also take some supplies into consideration, as molds for cement parts for instance, which are part of the rare needed “imports”, into consideration. At these costs, we must add expertise to define the proper pattern for local context, and the support of local players in their development of skills and their autonomy on the tool. It induces local assessment (technical, ecological and social), interactions with local authorities, communities and possible NGOs to converge towards a shared deployment scheme, local action for involvement and empowerment.

Thus, we estimate that :

- **Consulting, models, field concertation and training should be a standard package from a few dozen to a hundred thousand euros**. High complexity environment, with interaction with other works for instance, might make it more complicated, thus more expensive however.
- **Furniture, supply and production assistance** will vary with the site and structure size (the more it is wide and high, the more molds we will need). If molds can be produced on site, with assistance, price should be low to negligible regarding these. Otherwise, a few tens of thousands of euros would be required for these supplies according to the whole structure size.
- **Structure production and deployment can really vary** from site to site
  - If we settle one row, with local sourcing, and local involvement, cost will be really low (few hundreds of euros per m)

  - If we settle three or four rows, with engines and marine works, with high technology materials, … Then, in our estimate, costs might reach from 1500 to 4500 € per linear meter, which might not be competitive with traditional works costs.

However, it is important to note that ROOT primarily targets the first application case.

2.3 ROOT's expected benefits

We expect ROOT to provide 4 main types of benefits:

- ROOT main value is to **protect coastline against erosion** processes from waves and currents action. It is expected to be more flexible than traditional engineering solution, allowing small scale projects, additional settlement to large infrastructures, … ROOT reproduces mangrove effects in the local context, so ROOT would optimize mangrove settlement and growth on site, to build a Nature Based Solution on site, with all associated benefits.
  ROOT is an eco-engineered module, which **supports many ecological functionalities of mangrove environments:** nursery, habitat, shelter,… Thus ROOT enables local ecological restoration of some functions lost after mangrove destruction, and helps to generate local ecosystem services whom local communities will benefit from (various resources, fishes, shells, science, tourism …)
- As soon as it is settled, **ROOT maintains local sediments.** The structure will keep sediments on site, and **prevent carbon release from soil stocks,** which is estimated to 950t Ca / ha. Moreover, **ROOT will also help carbon capture.** As it aims at improving mangrove settlement, growth and survival rates, it will increase local carbon sequestration rates.
- Then, ROOT will also generate social and economic co-benefits. As mentioned above, ROOT relies on local empowerment and involvement. This model implies the incr**ease in competence of the local actors** and the organization **of the needed activities for the production** (exploitation of bamboos or another species, creation of mortar, metal or wood work, ...) or **for the management & exploitation** of the site (controls, maintenance of the structures, collection of halieutic resources, ...). It can support social balance, through women involvement for instance, or bring access to protein sources to nearby community with a simple conditioning of the collected resource.

Conclusion:

ROOT is an innovative Nature-based Solution that aims at mitigating hydrodynamic and sedimentary conditions to (1) control coastal erosion and (2) to restore favorable conditions for mangrove restoration through the spontaneous regeneration of mangrove trees. ROOT consists in a tool for ecological restoration but also in a social lever thanks to the ecosystem services generated by ROOT in terms of resource production (fish, shell…) and associated activities (deployment, maintenance…).. ROOT relies on affordable materials, production processes and deployment methodologies to empower and involve local communities in the fabrication, deployment, maintenance and management of the infrastructure. It supports many services from coastal protection to ecological functionalities, resources production, carbon sequestration, and its affordability should make it easy to transfer to local small communities. Currently under pilot experiment, the first results show performances that can reach up to 70% of energy dissipation for a 10 meter wide structure, It is reasonable to consider that this type of infrastructure could be 2 to 10 times cheaper than traditional grey infrastructure, whilst generating value for local communities, and therefore contributing to their sustainable settlement and development in coastal areas.

Références

Analyses bibliographique

- Alongi D. (2012), Carbon sequestration in mangrove forests, Journal of Carbon Management 3: 313-322.
- Balke T., T. Bouma, E. Horstman, E. Webb, P. Erftemeijer, and P. Herman (2011), Windows of opportunity: Thresholds to mangrove seedling establishment on tidal flats, Marine Ecology Progress Series 440: 1-9.
- Balke T., T. Bouma, P. Herman, E. Horstman, C. Sudtongkong, and E. Webb (2013), Cross-shore gradients of physical disturbance in mangroves: implications for seedling establishment, Biogeosciences 10: 5411-5419.
- Barbier E. et al. (2008), Coastal ecosystem-based management with nonlinear ecological functions and values, Science 319: 321–323.
- Booij N., R. Ris, and L. Holthuijsen (1999), A third-generation wave model for coastal regions, Part I, model description and validation, Journal of Geophysical Research C4(104): 7649-7666.
- Bradley K. and C. Houser (2009), Relative velocity of seagrass blades: Implications for wave attenuation in low-energy environments, Journal of Geophysical Research Earth Surface 114: 1-13.
- Bullock E., S. Fagherazzi, W. Nardin, P. Vo-Luong, P. Nguyen, and C. Woodcock (2017), Temporal patterns in species zonation in a mangrove forest in the Mekong Delta, Vietnam, using a time series of Landsat imagery, Continental Shelf Research 147: 114-154.
- Burcharth H., B. Zanuttigh, T. Andersen, J. Lara, G. Steendam, P. Ruol, P., ... P. Higuera (2015), Innovative engineering solutions and best practices to mitigate coastal risk, In Coastal Risk Management in a Changing Climate (pp. 55-170), Butterworth-Heinemann.
- Dalrymple R., J. Kirby, and P. Hwang (1984), Wave Diffraction due to areas of high energy dissipation, Journal of Waterway, Port, Coastal and Ocean Engineering 110: 67-79.
- Eldina F., A. Abd Wahab, and I. Hadibah (2008), Numerical modeling approach of an artificial mangrove root system (ArMS) submerged breakwater as wetland habitat protector, COPEDEC VII, 2008, Dubai, UAE.
- Fagherazzi S., K. Bryan, and W. Nardin (2017), Buried alive or washed away: the challenging life of mangroves in the Mekong delta, Oceanography 30(3): 48-59.
- Food and Agricultural Organization (FAO) of the United Nations (2007), The world's mangroves: a thematic study in the framework of the Global Forest Resources Assessment 2005, FAO forestry paper, 0258-6150, 153.
- Friedrichs C. (2011), Tidal flat morphodynamics: A synthesis, in Treatise on Estuarine and Coastal Science, edited by E. Wolanski and D. McLusky, chap. 3.06, pp. 137–170, Academic Press, Waltham, Mass.

- Gedan K., M. Kirwan, E. Wolanski, E. Barbier, and B. Silliman (2010), The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm, Climate Change 106: 7-29.
- Guiral D., J. Albaret, E. Baran, F. Bertrand, L. Loeuff, J. Montoroi, M. Sow (1999), Les écosystèmes de mangrove, In Rivières du Sud, Sociétés et Mangroves Ouest Africaines (vol.1), Edition IRD: Paris, 416 pages.
- Halide H., R. Brinkman, and P. Ridd (2004), Designing bamboo wave attenuators for mangrove plantations, Indian Journal of Marine Sciences 33: 220-225.
- Hunt S., K. Bryan, and J. Mullarney (2015), The influence of wind and waves on the existence of stable intertidal morphology in meso-tidal estuaries, Geomorphology 228: 158–174.
- Infantes E., A. Orfila, G. Simarro, J. Terrados, M. Luhar, and H. Nepf (2012) Effect of a seagrass (Posidonia oceanica) meadow on wave propagation, Marine Ecological Progress Series 456: 63-72.
- Ismail H., A. Abd Wahab, and N. Alias (2012), Determination of mangrove forest performance in reducing tsunami run-up using physical models, Natural Hazards 63: 939-963.
- Karim M., K. Tanimoto, and P. Hieu (2009), Modelling and simulation of wave transformation in porous structures using VOF based two-phase flow model, Applied Mathematical Modelling 33: 343-360.
- Kobayashi N., A. Raichle, and T. Asano (1993), Wave attenuation by vegetation, Journal of Waterway, Port, Coastal, and Ocean Engineering 119.
- Lewis R. (2005), Ecological engineering for successful management and restoration of mangrove forests, Ecological Engineering 24: 403-418.
- Lovelock C., B. Sorrell, N. Hancock, Q. Hua, and A. Swales (2010). Mangrove forest and soil development on a rapidly accreting shore in New Zealand, Ecosystems 13(3): 437-451.
- Luhar M., E. Infantes, and H. Nepf (2017), Seagrass blade motion under waves and its impact on wave decay, Journal of Geophysical Research Oceans 122: 3736-3752.
- Marchand M. (2008), Mangrove restoration in Vietnam: Key considerations and practical guide, Deltares Report T2666, 42 pages.
- Massel S., K. Furukawa, and R. Brinkman (1999), Surface wave propagation in mangrove forests, Fluid Dynamics Research 24: 219-249.
- Maza M. (2015), Experimental and numerical modelling of flow interaction with natural ecosystems for coastal protection, PhD thesis Universitad de Cantabria, 353 pages.
- McIvor A., I. Möller, T. Spencer, and M. Spalding (2012), Reduction of wind and swell waves by mangroves, Natural Coastal Protection Series: Report 1, Cambridge Coastal Research Unit Working Paper 40, Published by The Nature Conservancy and Wetlands International, 27 pages.
- Mendez F and I. Losada (2004), An empirical model to estimate the propagation of random breaking and nonbreaking waves over vegetation fields, Coastal Engineering 51: 103-118.

- Möller I., M. Kudella, F. Rupprecht, T. Spencer, M. Paul, B. van Wesenbeeck, G. Wolters, K. Jensen, T. Bouma, M. Miranda-Lange, S. Schimmels (2014), Wave attenuation over coastal salt marshes under storm surge conditions, Nature Geoscience 7: 727-731.
- Bernard Molina, Fabien Remy, Gwendoline Arnaud, Vincent Rey, Julien Touboul, Damien Sous (2016), On the dispersion equation for linear waves traveling through or over dense arrays of vertical cylinders
- Mullarney J., S. Henderson, J. Reyns, B. Norris, and K. Bryan (2017), Spatially varying drag within a wave-exposed mangrove forest and on the adjacent tidal flat, Continental Shelf Research 147: 102-113.
- Narayan S., M. Beck, B. Reguero, I. Losada, B. van Wesenbeeck, N. Pontee et al. (2016), The effectiveness, costs and coastal protection benefits of natural and nature-based defences, PLoS ONE 11(5): e0154735.
- Nardin W., C. Woodcock, and S. Fagherazzi. (2016), Bottom sediments affect Sonneratia mangrove forests in the prograding Mekong Delta, Vietnam, Estuarine, Coastal and Shelf Science 177:60-70.
- Nové-Josserand C., F. Castro Hebrero, L. Petit, W. Megill, R. Godoy-Diana, and B. Thiria (2018), Surface wave energy absorption by a partially submerged bio-inspired canopy, Bioinspiration & Biomimetics 13: 036006.
- Nowacki D., A. Beudin, N. Ganju (2017), Spectral wave dissipation by submerged aquatic vegetation in back-barrier estuary, Limnology and Oceanography 62: 736-753.
- Paul M. and C. Amos (2011), Spatial and seasonal variation in wave attenuation over Zostera noltii, Journal of Geophysical Research Oceans 116: 1-16.
- Quartel S., A. Kroon, P. Augustinus, P. Van Santen, and N. Tri (2007), Wave attenuation in coastal mangroves in the Red River Delta, Vietnam, Journal of Asian Earth Sciences 29(4): 576-584.
- Sanchez-Gonzalez J. , V. Sanchez-Rojas, and C. Memos (2011), Wave attenuation due to Posidonia oceanica meadows, Journal of Hydraulic Research 49: 503-514.
- Schmitt K., T. Albers, T. Pham, and S. Dinh (2013), Site-specific and integrated adaptation to climate change in the coastal mangrove zone of Soc Trang Province, Viet Nam, Journal of Coastal Conservation 17: 545-558.
- Scyphers S., S. Powers, K. Heck, and D. Byron (2011), Oyster reefs as natural breakwaters mitigate shoreline loss and facilitate fisheries, PLoS One 6(8): e22396.
- Strusinska-Correia A., S. Husrin, H. Oumeraci (2013), Tsunami damping by mangrove forest: a laboratory parameterized trees, Natural Hazards and Earth System Sciences 13: 483-503.
- Suzuki T., M. Zijlema, B. Burger, M. Meijer, and S. Narayanet (2012), Wave dissipation by vegetation with layer schematization in SWAN, Coastal Engineering 59: 64-71.
- Swales A., S. Bentley, and C. Lovelock (2015), Mangrove-forest evolution in a sediment-rich estuarine system: opportunists or agents of geomorphic change?, Earth Surface Processes Landforms, 40: 1672–1687.

- Tinoco R. and G. Coco (2016), A laboratory study on sediment resuspension within arrays of rigid cylinders, Advances in Water Resources 92: 1-9.
- van Maanen B., G. Coco, and K. Bryan (2015), On the ecogeomorphological feedbacks that control tidal channel network evolution in a sandy mangrove setting, Proceedings of the Royal Society A 471 : 20150115.
- Yang J., H. Chung, and H. Nepf (2016), The onset of transport in vegetated channels predicted by turbulent kinetic energy, Geophysical Research Letters 43(11): 261-268.
- Yang Y., J. Irish, and R. Weiss (2017), Impact of patchy vegetation on tsunami dynamics, Journal of Waterway, Port, Coastal, and Ocean Engineering 143.
- Zhang K., H. Liu, Y. Li, H. Xu, J. Shen, J. Rhome, and T. Smith (2012), The role of mangroves in attenuating storm surges, Estuarine, Coastal and Shelf Science 102-103: 11–23.

Tests en modèles physiques

- Chen, H., Ni, Y., Li, Y., Liu, F., Ou, S., Su, M., Peng, Y., Hu, Z., Uijttewaal, W., Suzuki, T. (2018) Deriving vegetation drag coefficients in combined wave-current flows by calibration and direct measurement methods ; Advances in Water Resources, 122, 217–227.
- Dalrymple, R.A., Kirby, J.T., Hwang, P.A. (1984) Wave diffraction due to areas of energy dissipation. Journal of Waterway Port Coastal and Ocean Engineering, 110(1), 67-79.
- Losada, I.J., Maza, M., Lara, J.L. (2016) A new formulation for vegetation-induced damping under combined waves and currents. Coastal Engineering, 107, 1–13.
- Molin, B., Remy, F., Arnaud, G., Rey V., Touboul, J., Sous, D. (2016) On the dispersion equation for linear waves traveling through or over dense arrays of vertical cylinders. Applied Ocean Research, 61, 148–155.
- Molin, B., Remy, F. (2016) An investigation of the resonant sloshing motion in a rectangular tank with multiple vertical cylinders. Actes des 15èmes Journées de L'Hydrodynamique, 22-24 Novembre 2016, Brest (France).

Tests en modèles numériques

- Anderson, M.E., Smith, J.M. (2014) Wave attenuation by flexible, idealized salt marsh vegetation. Coastal Engineering, 83, 82–92.
- Arnaud, G. (2016) Houle à la côte : propagation, impacts et ouvrages innovants. Thèse de doctorat de l'Université de Toulon/MOI, Toulon (France).

- Berkhoff, J.C.W. (1972) Computations of combined refraction-diffraction. Proc. 13th Int. Conf. on Coastal Engineering, ASCE, Vancouver (Canada), Chapter 24.
- Bradley, K., Houser, C. (2009) Relative velocity of seagrass blades: Implications for wave attenuation in low-energy environments. J. Geophys. Res., F Earth Surf., 114, https://doi.org/10.1029/2007JF000951
- Chen, H., Ni, Y., Li, Y., Liu, F., Ou, S., Su, M., Peng, Y., Hu, Z., Uijttewaal, W., Suzuki, T. (2018) Deriving vegetation drag coefficients in combined wave-current flows by calibration and direct measurement methods. Advances in Water Resources, 122, 217–227.
- Cheng, N.-S., Nguyen, H.T. (2011) Hydraulic radius for evaluating resistance induced by simulated emergent vegetation in open-channel flows. Journal of Hydraulic Engineering, 137, 995–1004.
- Dalrymple, R.A., Kirby, J.T., Hwang, P.A. (1984) Wave diffraction due to areas of energy dissipation. Journal of Waterway Port Coastal and Ocean Engineering, 110(1), 67-79.
- Hu, Z., Suzuki, T., Zitman, T., Uittewaal, W., Stive, M. (2014) Laboratory study on wave dissipation by vegetation in combined current-wave flow. Coastal Engineering, 88,131-142.
- Infantes, E., Orfila, A., Bouma, T.J., Simarro, G., Terrados, J. (2011) Posidonia oceanica and Cymodocea nodosa seedling tolerance to wave exposure. Limnol. Oceanogr., 56, 2223–2232. https://doi.org/10.4319/lo.2011.56.6.2223
- Jadhav, R.S., Chen, Q., Smith, J.M. (2013) Spectral distribution of wave energy dissipation by salt marsh vegetation. Coastal Engineering, 77, 99–107.
- Kagemoto, H., Murai, M., Saito, M., Molin, B., Malenica, S. (2002) Experimental and theoretical analysis of the wave decay along a long array of vertical cylinders. Journal of Fluid Mechanics, 456, 113–135.
- Keulegan, G.H., Carpenter L.H. (1958) Forces on cylinders and plates in oscillating fluid. Journal of Research of the National Bureau of Standards, 60(5), 423-440.
- Liu, P.L.F., Chang, C.W., Mei, C.C., Lomonaco, P., Martin, F.L., Maza, M. (2015) Periodic water waves through an aquatic forest. Coastal Engineering, 96, 100–117.
- Losada, I.J., Maza, M., Lara, J.L. (2016) A new formulation for vegetation- induced damping under combined waves and currents. Coastal Engineering, 107, 1–13.
- Luhar, M., Nepf, H.M. (2016) Wave-induced dynamics of flexible blades, Journal of Fluids and Structures, 61, 20-41.
- Maza, M. (2015) Experimental and numerical modelling of flow interaction with natural ecosystems for coastal protection. Thèse de doctorat Universitad de Cantabria, Santander (Espagne).
- Mei C.C., Chan I.C., Liu P.L.-F. (2014) Waves of intermediate length through an array of vertical cylinders, Environmental Fluid Mechanics, 14(1), 235-261.
- Mendez, F.J., Losada, I.J., Losada, M.A. (1999) Hydrodynamics induced by wind waves in a vegetation field. Journal of Geophysical Research. Oceans, 104(C8), 18 383–18 396

- Mendez, F.J., Losada, I.J. (2004) An empirical model to estimate the propagation of random breaking and nonbreaking waves over vegetation fields. Coastal Engineering, 51(2), 103–118.
- Morison, J.R., Johnson, J.W., Schaaf, S.A. (1950) The forces exerted by surface waves on piles. Journal of Petroleum Technology, 2, 149-154.
- Kobayashi, N., Raichle A., W., Toshiyuki, A. (1993) Wave attenuation by vegetation. Journal of Waterway Port Coastal and Ocean Engineering, 119, 30–48.
- Ozeren, Y., Wren, D.G., Wu, W. (2014) Experimental investigation of wave attenuation through model and live vegetation. Journal of Waterway, Port, Coastal, and Ocean Engineering, 140(5), 140. 04014019
- Suzuki, T., Zijlema, M., Burger, B., Meijer, M., Narayan, S. (2011) Wave dissipation by vegetation with layer schematization in SWAN. Coastal Engineering, 59, 64-71.
- Suzuki, T., Hu, Z., Kumada, K., Phan, L. K., Zijlema, M. (2019) Non-hydrostatic modeling of drag, inertia and porous effects in wave propagation over dense vegetation fields. Coastal Engineering, 149, 49-64.
- Wu, W.-C., Cox, D.T. (2015) Effects of wave steepness and relative water depth on wave attenuation by emergent vegetation. Estuarine, Coastal and Shelf Science, 164, 443-450.