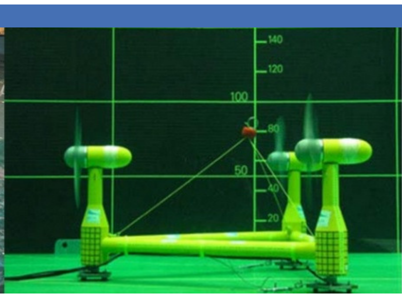
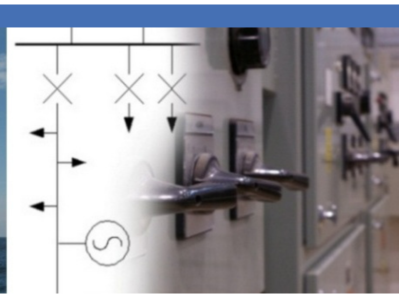
Marine Renewables Infrastructure Network



Infrastructure Access Report

Infrastructure: UNIFI-CRIACIV Wave-Current Flume

***User-Project*: FlexOWT-Wave**

Response Assessment of Flexible Parts of Offshore Wind Turbines subjected to Large Translations/Rotations due to Wave Loading

Aristotle University of Thessaloniki

Status: Final
Version: 02
Date: 28-Oct-2014

EC FP7 "Capacities" Specific Programme
Research Infrastructure Action

ABOUT MARINET

MARINET (Marine Renewables Infrastructure Network for emerging Energy Technologies) is an EC-funded network of research centres and organisations that are working together to accelerate the development of marine renewable energy - wave, tidal & offshore-wind. The initiative is funded through the EC's Seventh Framework Programme (FP7) and runs for four years until 2015. The network of 29 partners with 42 specialist marine research facilities is spread across 11 EU countries and 1 International Cooperation Partner Country (Brazil).

MARINET offers periods of free-of-charge access to test facilities at a range of world-class research centres. Companies and research groups can avail of this Transnational Access (TA) to test devices at any scale in areas such as wave energy, tidal energy, offshore-wind energy and environmental data or to conduct tests on cross-cutting areas such as power take-off systems, grid integration, materials or moorings. In total, over 700 weeks of access is available to an estimated 300 projects and 800 external users, with at least four calls for access applications over the 4-year initiative.

MARINET partners are also working to implement common standards for testing in order to streamline the development process, conducting research to improve testing capabilities across the network, providing training at various facilities in the network in order to enhance personnel expertise and organising industry networking events in order to facilitate partnerships and knowledge exchange.

The aim of the initiative is to streamline the capabilities of test infrastructures in order to enhance their impact and accelerate the commercialisation of marine renewable energy. See www.fp7-marinet.eu for more details.

Partners

Ireland
University College Cork, HMRC (UCC_HMRC)
Coordinator
Sustainable Energy Authority of Ireland (SEAI_OEDU)

Denmark
Aalborg Universitet (AAU)
Danmarks Tekniske Universitet (RISOE)

France
Ecole Centrale de Nantes (ECN)
Institut Français de Recherche Pour l'Exploitation de la Mer (IFREMER)

United Kingdom
National Renewable Energy Centre Ltd. (NAREC)
The University of Exeter (UNEXE)
European Marine Energy Centre Ltd. (EMEC)
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Norway
Sintef Energi AS (SINTEF)
Norges Teknisk-Naturvitenskapelige Universitet (NTNU)

DOCUMENT INFORMATION

Title	Response Assessment of Flexible Parts of Offshore Wind Turbines subjected to Large Translations/Rotations due to Wave Loading
Distribution	**Public**
Document Reference	MARINET-TA1-FlexOWT-Wave
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Infrastructure Accessed:	UNIFI-CRIACIV Wave-Current Flume
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REVISION HISTORY

Rev.	Date	Description	Prepared by (Name)	Approved By Infrastructure Manager	Status (Draft/Final)
01	21/10/14	Draft Version of Report for Infrastructure Manager Approval	Lamprini Pavlidou Evangelia Loukogeorgaki		Draft
02	28/10/14	Final version of Report reviewed by the Infrastructure Manager		Lorenzo Cappietti	Final

ABOUT THIS REPORT

One of the requirements of the EC in enabling a user group to benefit from free-of-charge access to an infrastructure is that the user group must be entitled to disseminate the foreground (information and results) that they have generated under the project in order to progress the state-of-the-art of the sector. Notwithstanding this, the EC also state that dissemination activities shall be compatible with the protection of intellectual property rights, confidentiality obligations and the legitimate interests of the owner(s) of the foreground.

The aim of this report is therefore to meet the first requirement of publicly disseminating the knowledge generated through this MARINET infrastructure access project in an accessible format in order to:

- progress the state-of-the-art
- publicise resulting progress made for the technology/industry
- provide evidence of progress made along the Structured Development Plan
- provide due diligence material for potential future investment and financing
- share lessons learned
- avoid potential future replication by others
- provide opportunities for future collaboration
- etc.

In some cases, the user group may wish to protect some of this information which they deem commercially sensitive, and so may choose to present results in a normalised (non-dimensional) format or withhold certain design data – this is acceptable and allowed for in the second requirement outlined above.

ACKNOWLEDGEMENT

The work described in this publication has received support from MARINET, a European Community - Research Infrastructure Action under the FP7 “Capacities” Specific Programme.

LEGAL DISCLAIMER

EXECUTIVE SUMMARY

The successful development of Offshore Wind Turbines (OWTs) for shallow and/or deep water applications requires the efficient handling of various design challenges. An OWT presents a flexible structural system operating in a harsh environment; so, it may easily experience LArge Translations and large Rotations (LATR) under static and/or dynamic wind/wave loading. Thus, a new challenge appears related to OWTs' analysis tools. Specifically, for achieving a more accurate dynamic response assessment of OWTs, further development of existing Finite Element Numerical Models (FENM) is required, in terms of including the "LATR" (geometrical nonlinearity) aspect. Motivated by this, the project's User Group has recently developed a FENM that considers beam structural elements undergoing LATR and can be used for the efficient modeling of OWT's specific parts (e.g. tower, monopile support structure, mooring lines). For validating and enhancing this FENM, appropriate experiments are required.

This specific report aims to describe small-scale experimental work carried out in order to investigate and assess the dynamic response of parts of OWTs separately (e.g. monopile support structure of a fixed bottom OWT, components undergoing LATR that can be used for motion control of a floating OWT and/or for wave energy extraction additionally to the offshore wind exploitation, i.e. hybrid floating energy system) under the action of regular waves. In order to achieve this, five different model configurations were considered. The first two model configurations are used in order to assess the dynamic response of the tower and the support structure of a fixed-bottom OWT, while the other three configurations are applied for evaluating the response of parts of an OWT undergoing LATR as mentioned above.

The data collected will be used for the validation and the enhancement of a Finite Element Numerical Model (FENM) that considers beam structural elements undergoing LATR and has been recently developed by the present User Group as mentioned previously.

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1 INTRODUCTION & BACKGROUND

1.1 INTRODUCTION

The successful development of Offshore Wind Turbines (OWTs) for shallow and/or deep water applications requires the efficient handling of various design challenges. An OWT presents a structural system operating in a harsh environment; so, it may easily experience LArge Translations and large Rotations (LATR) under static and/or dynamic wind/wave loading. Thus, a new challenge appears related to OWTs' analysis tools. Specifically, for achieving a more accurate dynamic response assessment of OWTs, further development of existing Finite Element Numerical Models (FENM) is required, in terms of including the "LATR" (geometrical nonlinearity) aspect.

1.2 DEVELOPMENT SO FAR

The User Group has recently developed a FENM that considers beam structural elements undergoing LATR and can be used for the efficient modelling of OWT's specific parts (e.g. tower, monopile support structure, mooring lines). For validating and enhancing this FENM, appropriate experiments are required.

This project focuses on the implementation of small scale experiments for assessing the response of an OWT's specific parts undergoing LATR under the action of regular waves and for supporting the aforementioned FENM validation.

1.2.1 Stage Gate Progress

Previously completed: ✓
Planned for this project: ➲

STAGE GATE CRITERIA	Status
Stage 1 – Concept Validation	
• Linear monochromatic waves to validate or calibrate numerical models of the system (25 – 100 waves)	➲
• Finite monochromatic waves to include higher order effects (25 –100 waves)	
• Hull(s) sea worthiness in real seas (scaled duration at 3 hours)	
• Restricted degrees of freedom (DofF) if required by the early mathematical models	
• Provide the empirical hydrodynamic co-efficient associated with the device (for mathematical modelling tuning)	
• Investigate physical process governing device response. May not be well defined theoretically or numerically solvable	➲
• Real seaway productivity (scaled duration at 20-30 minutes)	
• Initially 2-D (flume) test programme	➲
• Short crested seas need only be run at this early stage if the devices anticipated performance would be significantly affected by them	
• Evidence of the device seaworthiness	
• Initial indication of the full system load regimes	
Stage 2 – Design Validation	
• Accurately simulated PTO characteristics	
• Performance in real seaways (long and short crested)	
• Survival loading and extreme motion behaviour.	➲

STAGE GATE CRITERIA	Status
• Active damping control (may be deferred to Stage 3)	
• Device design changes and modifications	
• Mooring arrangements and effects on motion	
• Data for proposed PTO design and bench testing (Stage 3)	
• Engineering Design (Prototype), feasibility and costing	
• Site Review for Stage 3 and Stage 4 deployments	
• Over topping rates	
Stage 3 – Sub-Systems Validation	
• To investigate physical properties not well scaled & validate performance figures	
• To employ a realistic/actual PTO and generating system & develop control strategies	
• To qualify environmental factors (i.e. the device on the environment and vice versa) e.g. marine growth, corrosion, windage and current drag	
• To validate electrical supply quality and power electronic requirements.	
• To quantify survival conditions, mooring behaviour and hull seaworthiness	
• Manufacturing, deployment, recovery and O&M (component reliability)	
• Project planning and management, including licensing, certification, insurance etc.	
Stage 4 – Solo Device Validation	
• Hull seaworthiness and survival strategies	
• Mooring and cable connection issues, including failure modes	
• PTO performance and reliability	
• Component and assembly longevity	
• Electricity supply quality (absorbed/pneumatic power-converted/electrical power)	
• Application in local wave climate conditions	
• Project management, manufacturing, deployment, recovery, etc	
• Service, maintenance and operational experience [O&M]	
• Accepted EIA	
Stage 5 – Multi-Device Demonstration	
• Economic Feasibility/Profitability	
• Multiple units performance	
• Device array interactions	
• Power supply interaction & quality	
• Environmental impact issues	
• Full technical and economic due diligence	
• Compliance of all operations with existing legal requirements	

1.2.2 Plan For This Access

The FlexOWT-Wave access project at UNIFI-CRIACIV Wave-Current Flume was planned in order to investigate and assess the dynamic response of parts of OWTs separately (e.g. monopile support structure of a fixed bottom OWT, components undergoing LATR that can be used for motion control of a floating OWT and/or for wave energy extraction additionally to the offshore wind exploitation (hybrid floating energy system) under the action of regular waves. The high quality data collected will be used for the validation and the enhancement of a FENM that considers beam structural elements undergoing LATR and has been recently developed by the present User Group. This represents the short-term objective of the present access project.

Thereinafter, the medium-term objective of the project is the incorporation of the validated and enhanced FENM into existing numerical tools related to the integrated analysis of fixed OWTs and, especially, of floating OWTs. As an outcome, the existing numerical tools will be enhanced and will enable a more accurate assessment of the dynamic response of OWTs considering the inclusion of flexible parts of OWTs undergoing LATR (geometrical nonlinearity consideration). This latter issue corresponds to the long-term objective of the project.

2 OUTLINE OF WORK CARRIED OUT

2.1 SETUP

2.1.1 The physical models

As mentioned above, the objective of the present experimental work is the assessment of the dynamic response (displacements/internal loads) of specific parts of OWTs, separately, under the action of regular waves. In order to achieve this, two different physical models were considered and different sets of experiments were implemented at the UNIFI-CRIACIV Wave-Current Flume. The first model (Model 1) is used in order to assess the dynamic response of the tower and the support structure of a fixed-bottom OWT, while the second one (Model 2) is applied for evaluating the response of parts of an OWT undergoing LATR (components that can be used for motion control of a floating OWT and/or for wave energy extraction additionally to the offshore wind exploitation, i.e. hybrid floating energy system). In the case of Model 1, two different model configurations were considered (Model configurations M1.1 and M1.2), while in the case of Model 2, three model configurations were used (Model configurations M2.1, M2.2 and M2.3). These model configurations are described in detail in the following sub-sections.

2.1.1.1 Model Configuration M1.1 (Model 1, configuration 1)

The first physical model configuration was a cantilever beam of circular cross section designed and constructed at UNIFI-CRIACIV Wave-Current Flume from members of the Access Provider Party with the aim to replicate an OWT's monopole support structure and tower at a geometrical scale of 1:60. The physical model (Figure 1) had height equal to 1.42m, outside diameter equal to 0.1m and thickness equal to 0.002m (internal diameter equal to 0.096m). The tested model was rigidly mounted at a base consisting of three base plates. Each base plate had a thickness equal to 0.02m. The material of both the beam and the base was perspex of specific weight equal to 1119kg/m^3 and Young module of Elasticity equal to 3.3*10^{6}N/m^2.

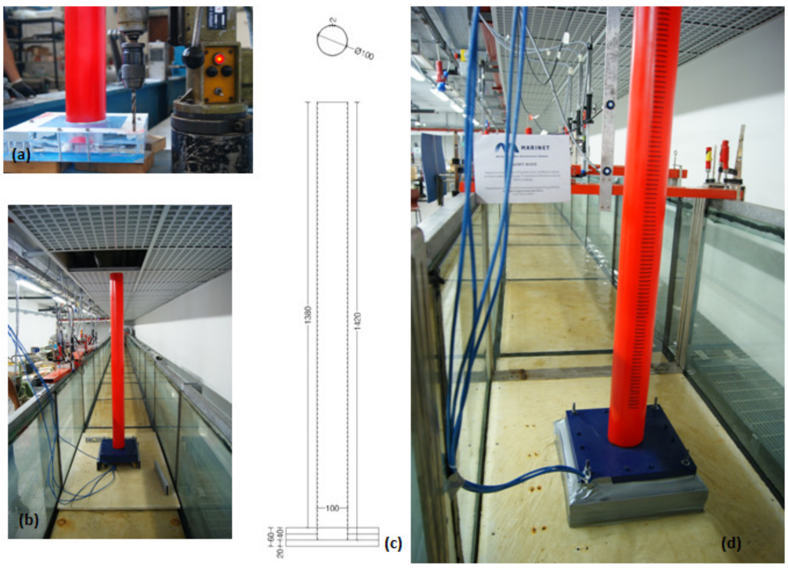

Figure 1: Sketch (c) and images (a, b and d) during construction and installation of the model configuration M1.1

2.1.1.2 Model Configuration M1.2 (Model 1, Configuration 2)

The above physical model was also tested under the action of two “point” masses mounted at specific positions along the length of the cantilever beam. In this way, model configuration M1.2 was achieved. The goal of applying the model configuration M1.2 was the assessment of the dynamic behaviour of the scaled model with natural frequencies closer to the frequencies of a tower prototype. The first “point” mass was placed at the top of the tower and had weight equal to 10.496kg. The second “point” mass was installed 0.45m lower than the first mass and had weight equal to 12.370kg. The material of the two point masses was steel with specific gravity equal to 7850 kg/m^3. The positions and the characteristics of the two “point” masses were defined through the application of a structural dynamic software from members of the Access Provider Party and are illustrated in Figure 2.

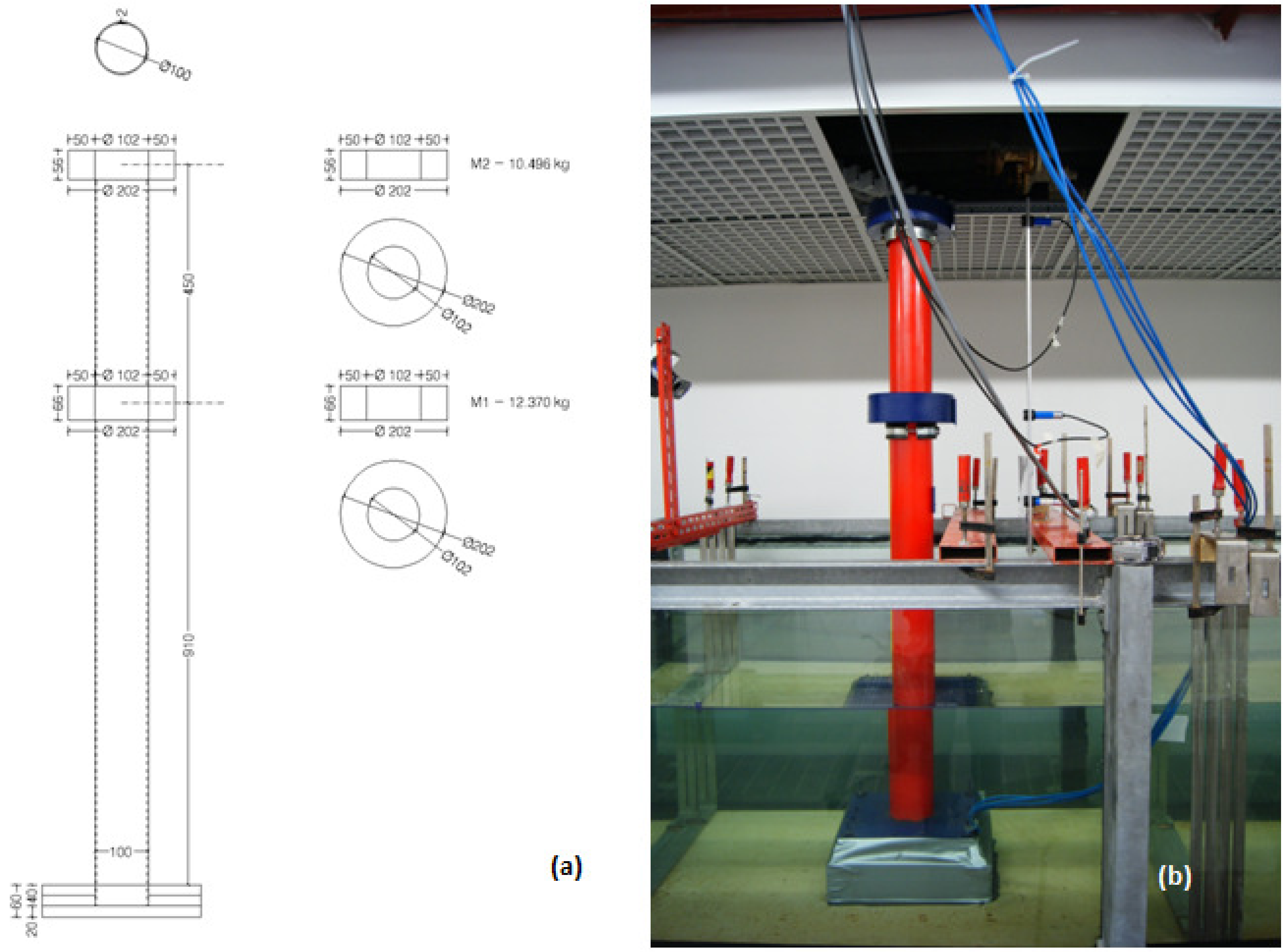

Figure 2: Sketch (a) and image (b) during construction and installation of the M1.2 model configuration

2.1.1.3 Model Configuration M2.1 (Model 2, Configuration 1)

To investigate the performance of parts of the OWTs undergoing LATR under wave loading, a second model was applied. The beam of the second physical model (Figure 3a) had a length equal to 0.80m, outside diameter equal to 0.03m and thickness equal to 0.001m (internal diameter equal to 0.028m). The material of the beam was aluminum with specific weight equal to 2823.08kg/m^3.

A pin-joint placed at specific position along the beam allowed the tested model to perform large rotations under the wave action. Specifically, the beam was mounted through the pin-joint on a circular wooden rigid base (Figure 3b). Then, at the top of the beam two linear springs were attached. The initial elongation of the springs was achieved through the mounting of the two free ends of the springs (the ends not attached to the beam) at frames that were installed on the wooden base (Figure 3d). The stiffness of each spring was equal to 110N/m.

The rigid base was placed at a height of 0.85m above the bottom of the wave flume (Figure 3c). In this way, the beam was suspended above the bottom of the wave flume (Figure 3c). The length of the beam inside the water for this model configuration was equal to 0.15m.

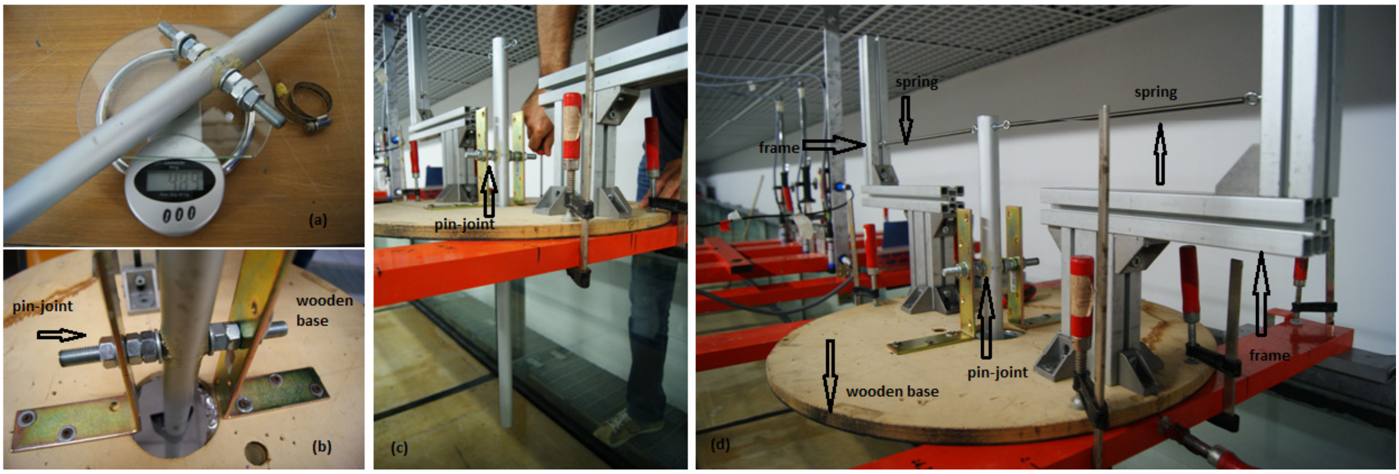

Figure 3: Details (a)-(c) and installation (d) of the model configuration M2.1

2.1.1.4 Model Configuration M2.2 (Model 2, Configuration 2)

In order to decrease the wave damping effect on the response of the beam of Model 2, configuration M2.2 was considered. This configuration was formed based on configuration M2.1 by decreasing the length of the beam inside the water from 0.15m (Configuration M2.1) to 0.10m (Configuration M2.2). This was achieved by raising the rigid base of the physical model at a height of 0.9m above the bottom of the wave flume (Figure 4a).

2.1.1.5 Model Configuration M2.3 (Model 2, Configuration 3)

In an effort to optimize the position of configuration M2.1 and more specifically, in order to achieve larger rotations around the pin-joint, the configuration M2.3 was formed by placing the rigid base of the physical model at a height of 0.82m above the wave flume bottom (Figure 4b-4c). The length of the beam inside the water was increased from 0.15m (Configuration M2.1) and 0.10m (Configuration M2.2) to 0.18m (Configuration M2.3).

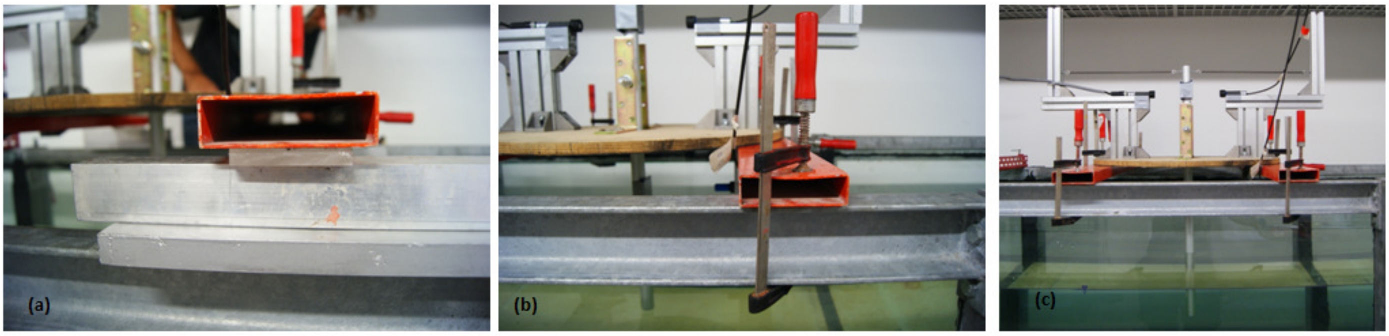

Figure 4: Variation of rigid base's vertical position for the formation of model configurations: M2.2 (a) M2.3 (b and c)

2.1.2 The Wave Flume

The experimental activities conducted at the UNIFI-CRIACIV Wave-Current Flume of the Maritime Engineering Laboratory of the Civil and Environmental Department of Florence University. Regarding the infrastructure specifications, the flume has length of 36m, width of 0.80m and depth of 0.80m. The wave generation in the flume is achieved with a computer-controlled piston-type wave capable to perform strokes up to 1600mm. For achieving sufficient wave dissipation of the incident waves, an artificial sloping beach made of rocks was constructed at a distance equal to 31.7m opposite of the wave-maker. This sloping beach had a slope equal to 1:3.7 and it is combined with the existing 1:2.25 bending ramp at the end of the flume (Figure 5).

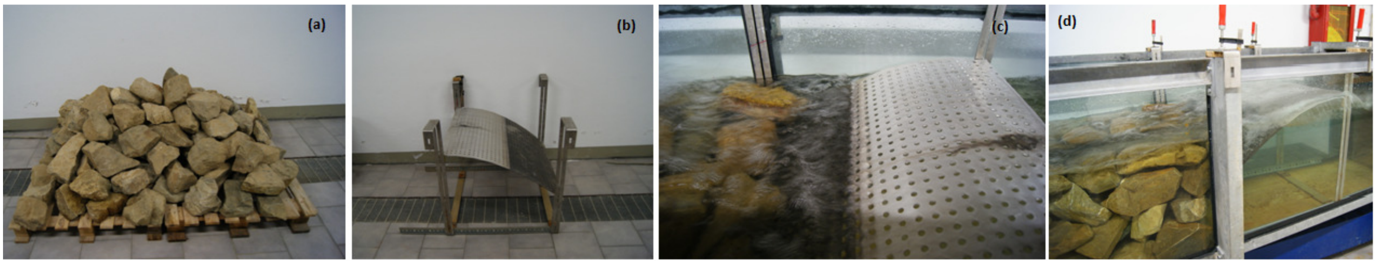

Figure 5: Absorbing Beach: material (a), bending ramp (b), total view (c, d)

2.1.3 The measuring equipment for configurations M1.1 and M1.2

The position of the physical model in the wave tunnel was chosen so that: (a) full development of the incident waves is ensured and (b) possible effects from the absorbing beach are avoided. Based on the physical model's position, the position of the equipment for measuring the wave field in the seaward side of the model was determined. Specifically, three contactless ultrasonic wave gauges (WG1, WG2, WG3), with a horizontal distance between them equal to 0.3m, were placed horizontally in front of the model, along the longitudinal axis of the flume, for measuring the wave field in this side of the model (Figure 7, Figure 8). The distance of WG3 from the model axis was 0.965m.
In order to measure the displacements along the length of the tower, three contactless ultrasonic wave gauges (WG4, WG5, WG6) were installed parallel to the longitudinal axis of the tower model in order to measure the displacements of the tower under the wave action (Figure 7, Figure 9). From upwards to downwards, the distance between WG6 and WG5 was equal to 0.45m and the distance between WG5 and WG4 was equal to 0.20m. WG6 was placed at a level where the tower top is, i.e. 1.54m from the bottom of the flume. Moreover, two cameras were used additionally to WG4-WG6 for the video recording of the performance of the model (Figure 10).
In order to measure the vertical forces and calculate the bending moments at the bottom of the physical model, four mono axial load cells were installed in the base, where the tower was mounted (Figure 6).

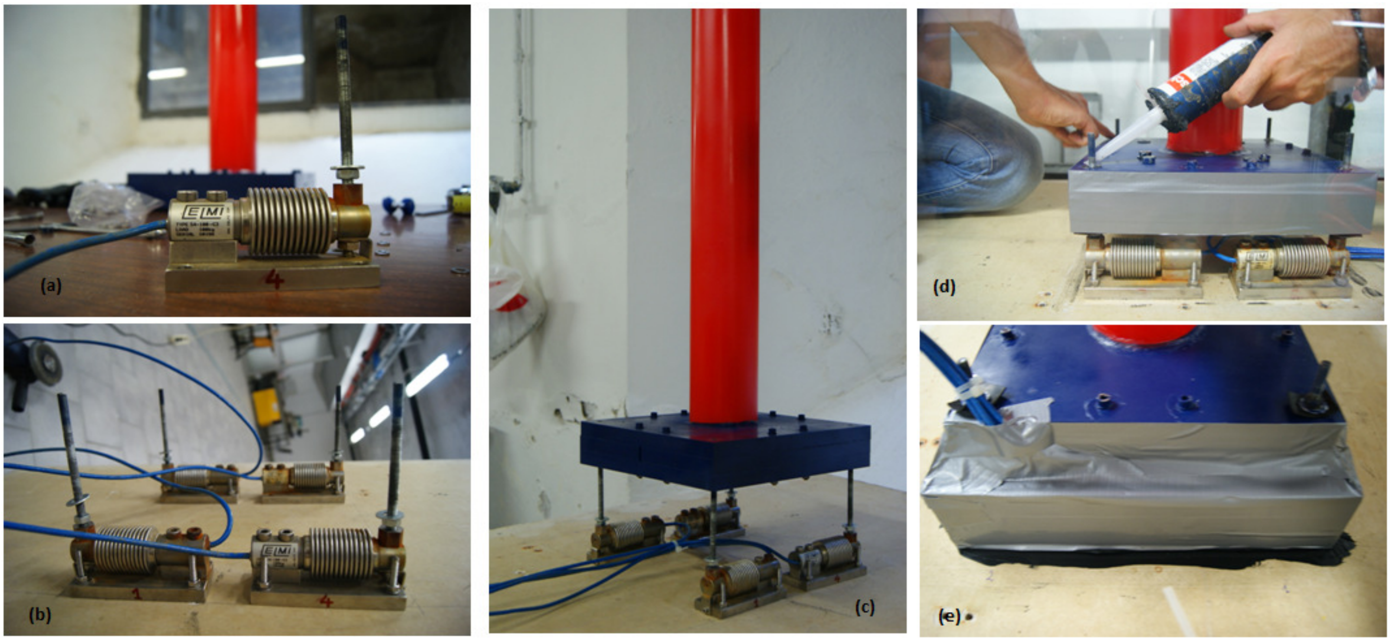

Figure 6: Installation of the load cells for model configurations M1.1 and M1.2

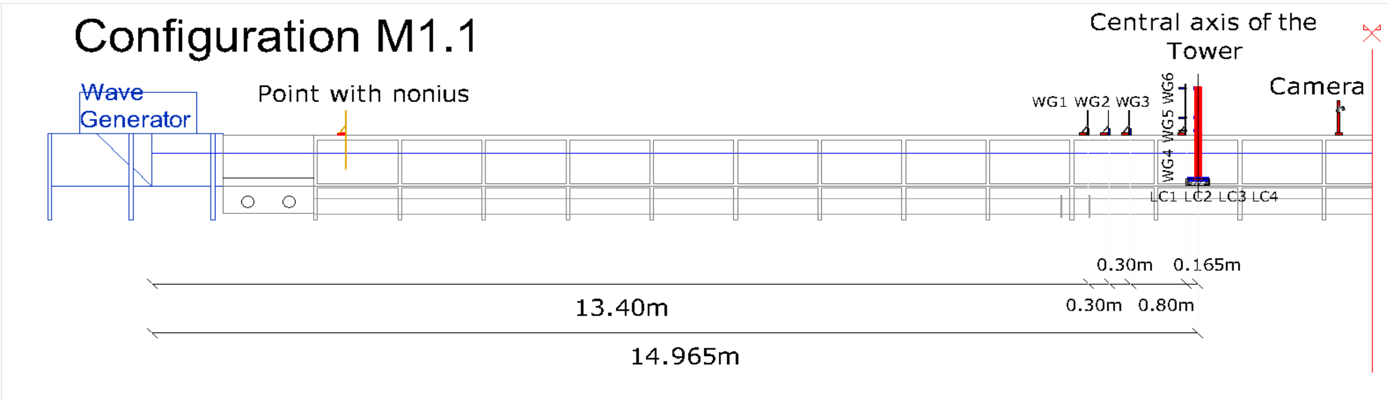

Figure 7: Experimental set-up for model configuration M1.1 (including the physical model and the measuring equipment)

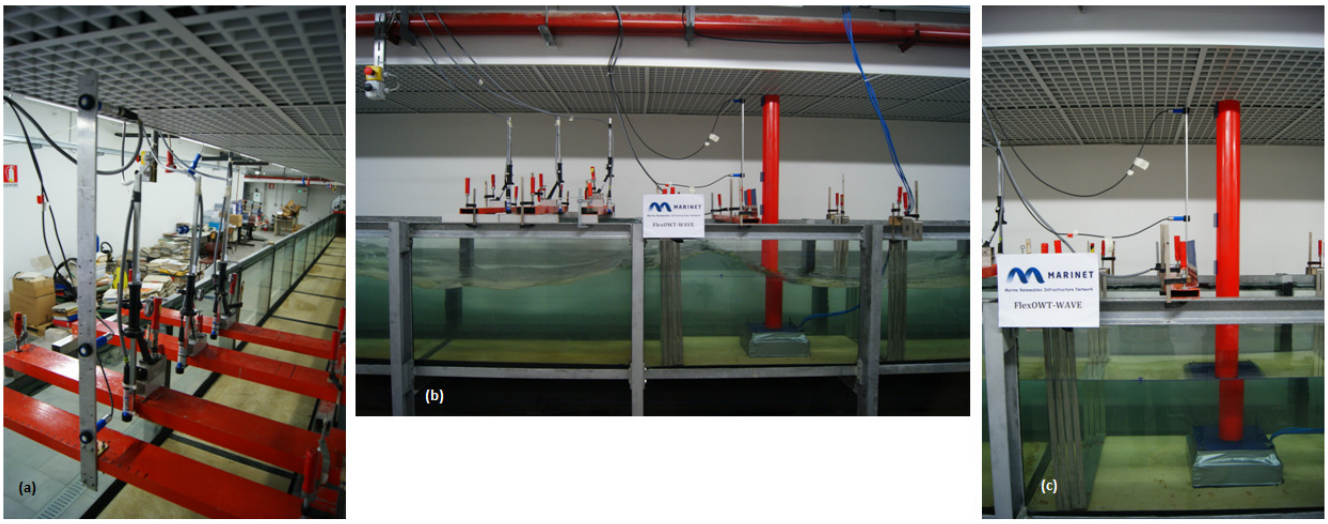

Figure 8: Measuring equipment for model configuration M1.1

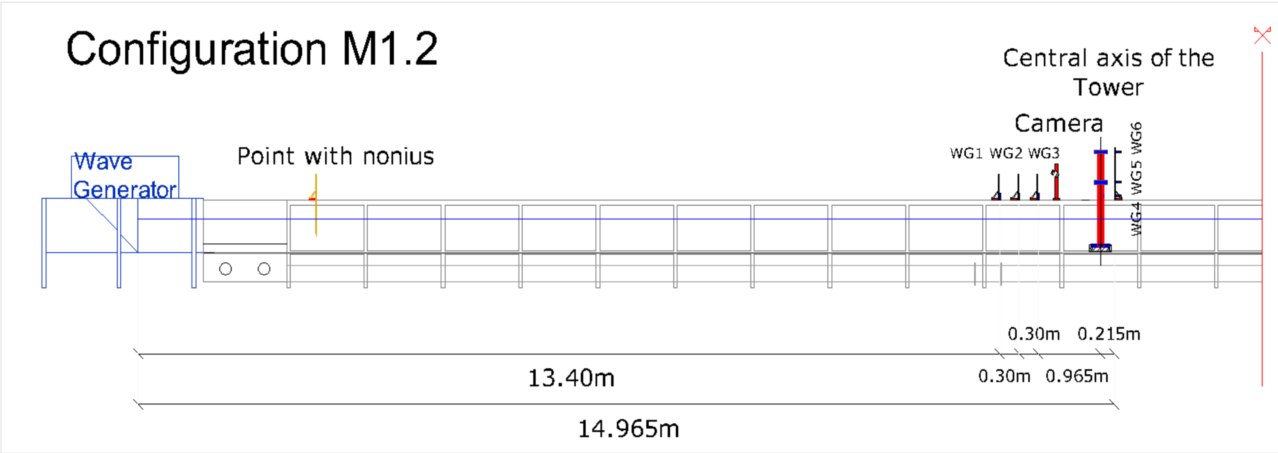

Figure 9: Experimental set-up for model configuration M1.2 (including the physical model and the measuring equipment)

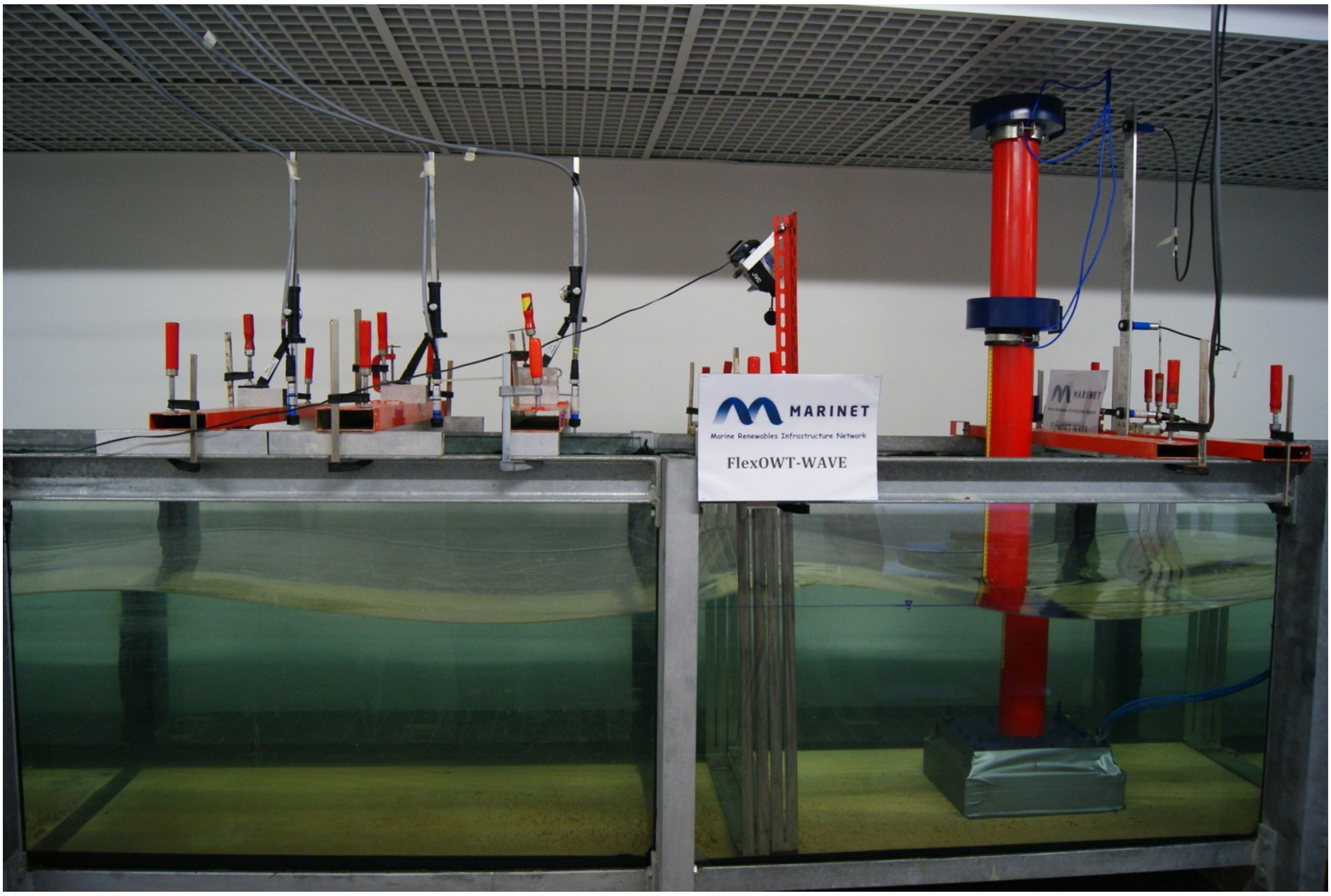

Figure 10: Measuring equipment for model configuration M1.2 (one camera is shown in this picture)

2.1.4 The measuring equipment for configurations M2.1~M2.3

The second physical model was installed at the same position in the wave flume as the first one. WG1~WG3 measuring the wave field remained in the same position as well. However, WG4~WG6, measuring the displacements of the physical model, were installed as shown in Figure 11 and Figure 12.

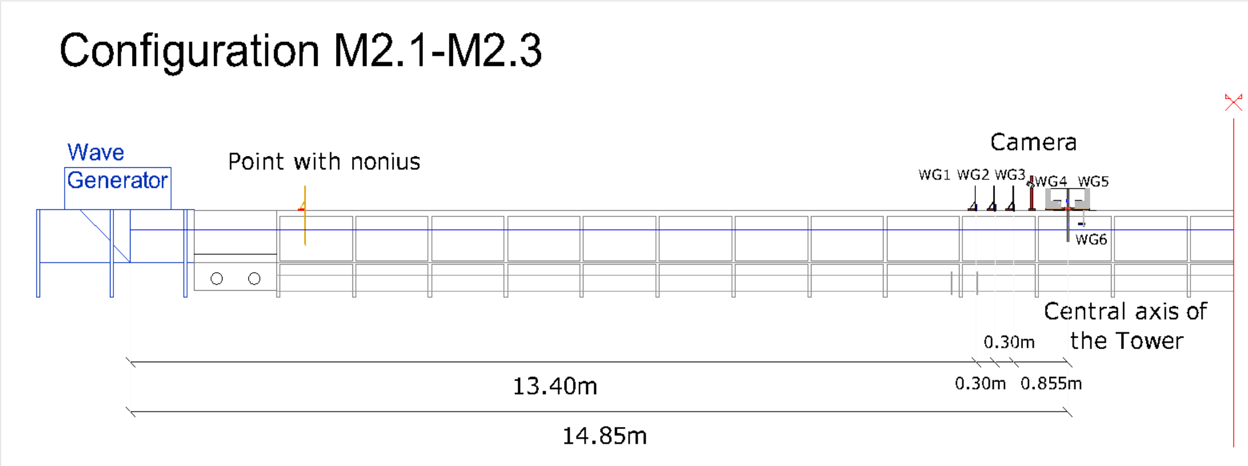

Figure 11: Experimental set-up for model configurations M2.1~M2.3 (including the physical model and the measuring equipment)

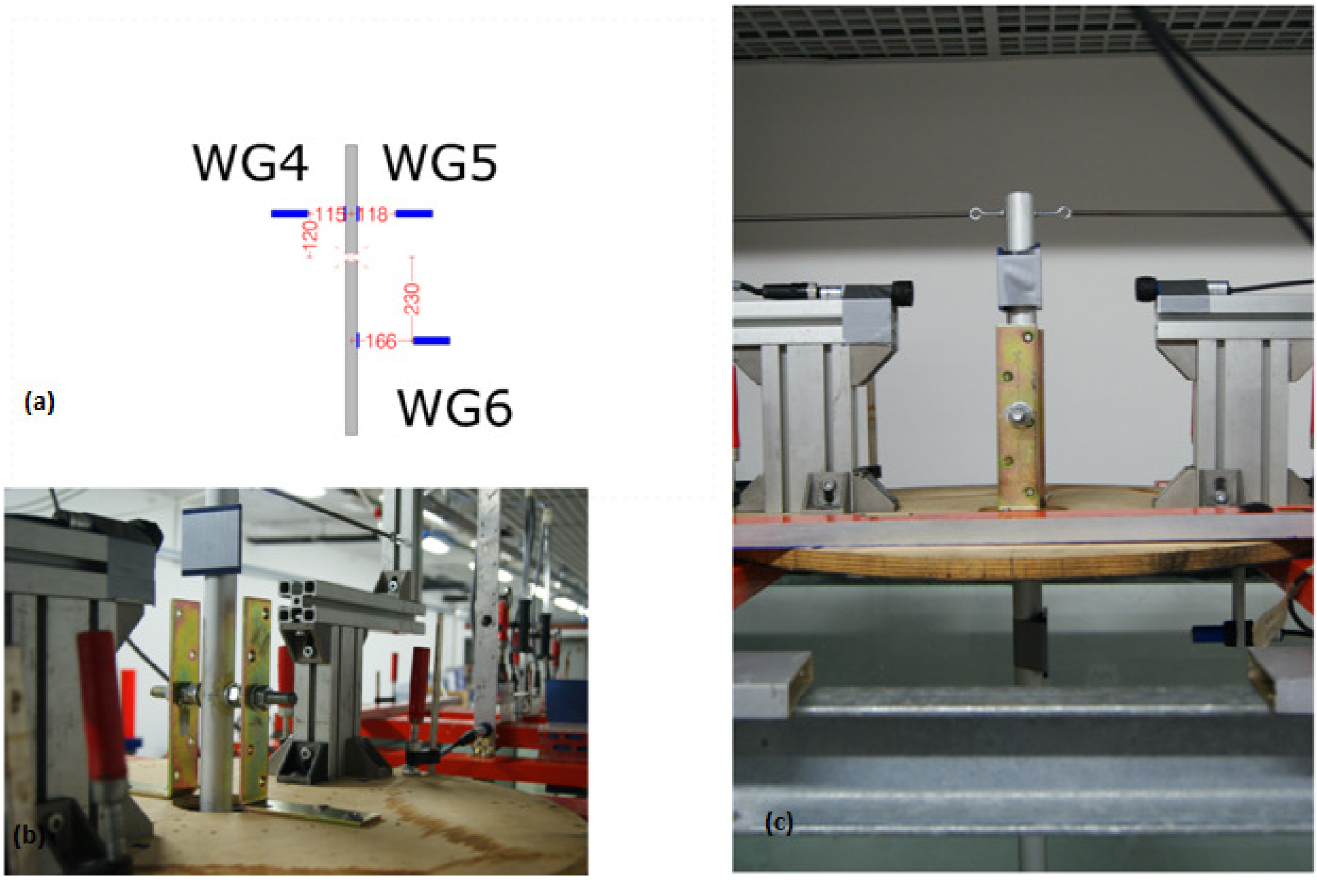

Figure 12: Sketch (a) and images (b, c) of the position of the WG4~WG6 for measuring the displacements of model configurations M2.1~M2.3

2.2 TESTS

2.2.1 Test Plan

The set of experiments of Model 1 was implemented for a geometrical scale equal to 1:60, while for Model 2 this scale was equal to 1:25. In both cases, the water depth was considered equal to 0.5m. The maximum allowable wave height to be generated is approximately 0.35m within a period range of 1-2s. Based on this, the periods were defined appropriately in order to achieve the goal of simulating deep water wave conditions for Model 1 and deep and intermediate water wave conditions for Model 2. The calculation of the regular wave characteristics was made as follows: Initially, three different wave heights (H) were considered to be examined and the values of these wave heights were defined. Then, for each wave height, four wave periods (T) were defined in order to take into account twelve different values of wave steepness (H/L). The characteristics of the waves considered in the present experimental investigation are shown in Table 1. Based on the above, twelve regular wave cases were totally examined for M1.1, M1.2 and M2.1. As far as model configurations M2.2 and M2.3, these configurations were examined only for three regular wave cases corresponding to the smallest wave period for each H value. The characteristics of the tests implemented are summarized in the Tables 1 and 2.

Wave Case	Wave Height, H(m)	Wave Period, T(s)	Wave Length, L(m)	H/L
H01	0.06	0.9	1.248	0.048
H02		1.1	1.781	0.034
H03		1.3	2.311	0.026
H04		1.5	2.826	0.021
H05	0.12	0.9	1.248	0.096
H06		1.1	1.781	0.067
H07		1.3	2.311	0.052
H08		1.5	2.826	0.042
H09	0.18	1.2	2.048	0.088
H10		1.3	2.311	0.078
H11		1.4	2.571	0.070
H12		1.6	3.078	0.058

Table 1: Regular wave characteristics (target values)

	M1.1	M1.2	M2.1	M2.2	M2.3
H01	+	+	+	+	+
H02	+	+	+		
H03	+	+	+		
H04	+	+	+		
H05	+	+	+	+	+
H06	+	+	+		
H07	+	+	+		
H08	+	+	+		
H09	+	+	+	+	+
H10	+	+	+		
H11	+	+	+		
H12	+	+	+		

Table 2: Tests implemented for each model configuration

2.3 RESULTS

Up to now, the obtained experimental data have been processed and analyzed at a preliminary stage. Indicative time series are included below, illustrating the time variation of quantities measured during the implemented experiments. Figure 13 shows part of the time series of the total vertical force (sum of the vertical forces measured by the four load cells) for M1.2 and for wave cases H05 and H10. Figure 14 presents a comparison in terms of the displacements measured by WG5 in the case M2.1 and M2.3 for the wave case H09. Figure 15 presents a comparison of the displacements measured by WG5 in the case of M2.1 for different wave conditions (wave cases H05 and H10).

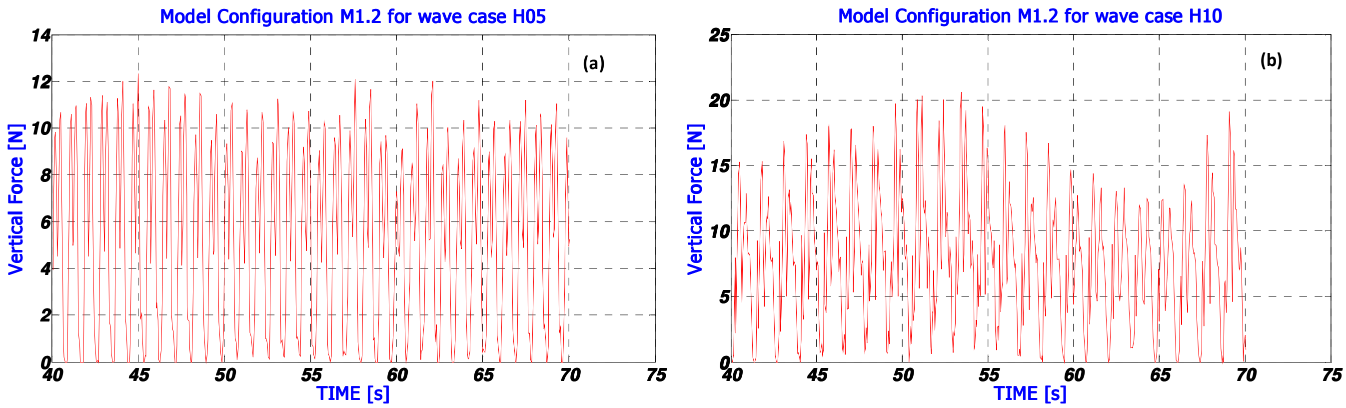

Figure 13: Time variation of total vertical force for M1.2 for wave cases H05 (a) and H10 (b)

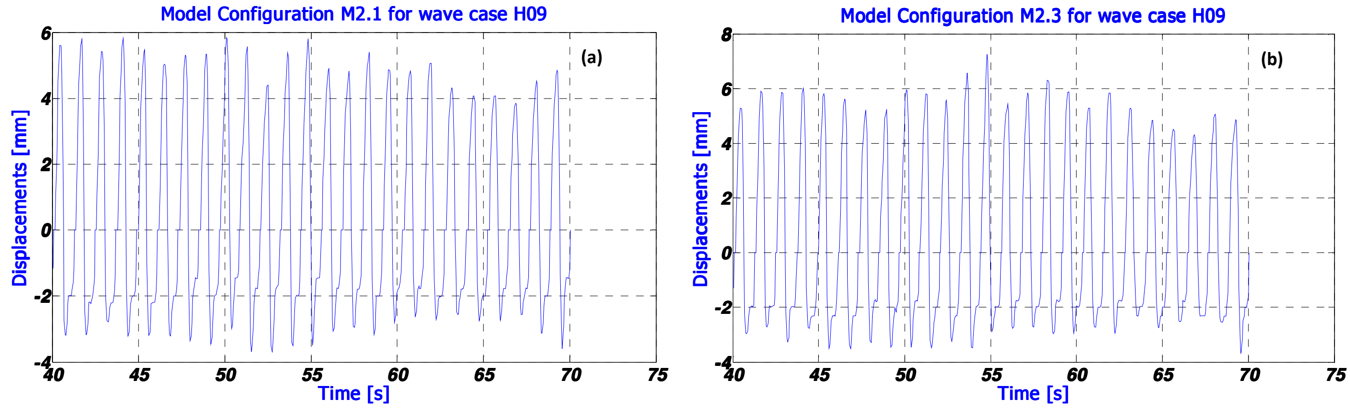

Figure 14: Time variation of measured displacements by WG5 for wave case H09 and for M2.1 (a) and for M2.3 (b)

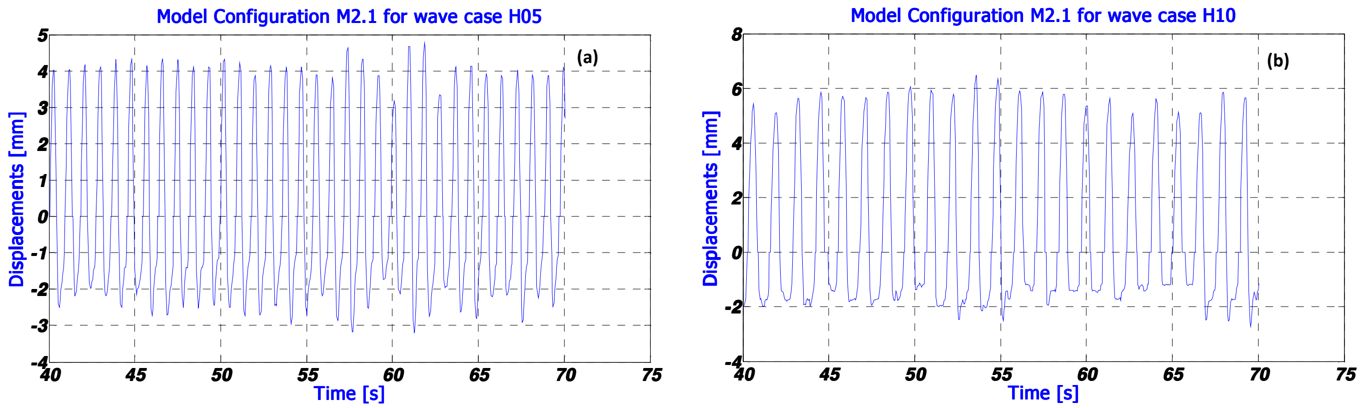

Figure 15: Time variation of measured displacements by WG5 for M2.1 and for wave cases H05 (a) and H10 (b)

Indicative results of preliminary analysis of the obtained data are also shown in the following figures. These figures include the variation of quantities (total vertical force, displacements) measured during the implemented experiments and the variation of the angle of rotation for Model 2 as a function of H/L. The later quantity (angle of rotation) has been calculated based on the obtained measurements (displacements). The examined quantities are expressed in terms of Root Mean Square (RMS) values and in terms of the mean value of the 1/3 maximum values of the obtained time series.

More specifically, Figure 16a shows the variation of the RMS (V_{RMS}) and 1/3 ($V_{1/3}$) values of the total vertical force as a function of H/L in the case of M1.2 for all examined wave cases. For the same model configuration and wave cases, Figure16b depicts the variation of the RMS (u_{RMS}) and 1/3 ($u_{1/3}$) values of the displacements measured by WG4 as a function of H/L. Figure 17 presents the variation of the RMS (ϕ_{RMS}) and 1/3 ($\phi_{1/3}$) values of the rotation angle calculated according to the displacements measured by WG5 in the case of M2.3 for all examined wave cases. Finally, Figure 15 presents a comparison of ϕ_{RMS} and $\phi_{1/3}$ values calculated based on the displacements measured by WG5 in the cases of M2.1, M2.2 and M2.3 for wave cases H01, H05 and H10.

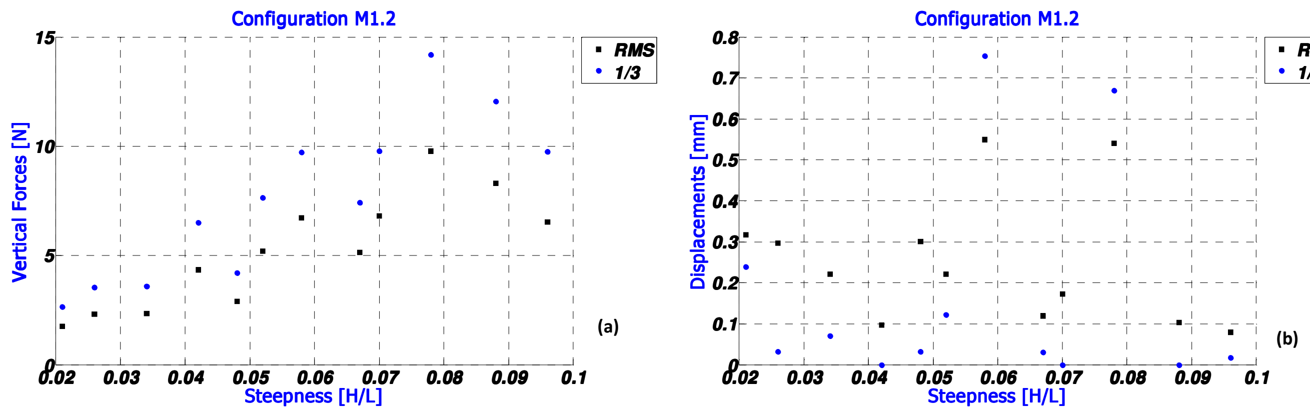

Figure 16: Variation of (a) V_{RMS} and $V_{1/3}$ and (b) u_{RMS} and $u_{1/3}$ (WG4) for M1.2 as a function of H/L for all examined wave cases

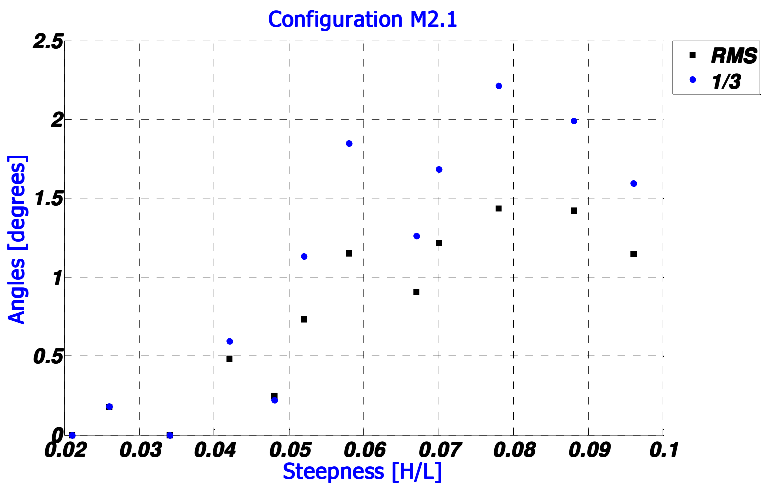

Figure 17: Rotation angles (RMS and maximum 1/3 values) calculated for M2.1 as a function of H/L for all examined wave cases

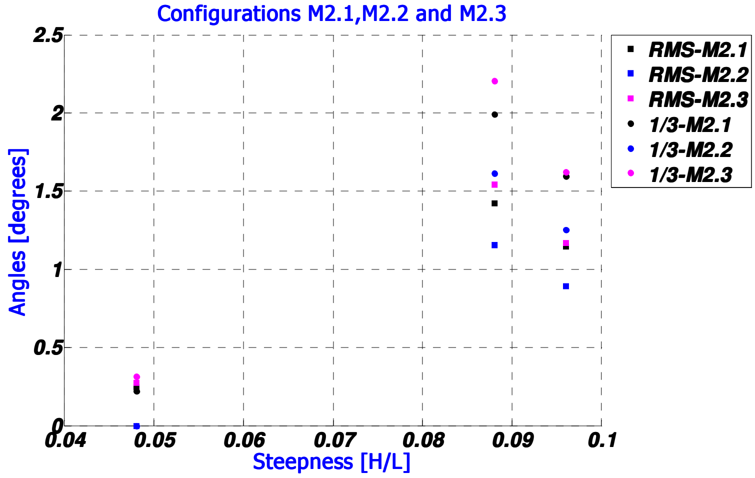

Figure 18: Rotation angles calculated (RMS and maximum 1/3 values) for M2.1, M2.2 and M2.3 as a function of H/L for wave cases H01, H05 and H09

2.4 Analysis & Conclusions

1. Time series of data concerning the dynamic response of different parts of OWTs under different regular wave conditions were obtained.
2. The set of experiments conducted for model configurations M1.1 and M1.2 allowed a useful insight into the behaviour of the OWT's tower including the monopile support structure.
3. The dependency between the dynamic response and the incident wave period and steepness was investigated. It was found that the aforementioned response is more affected by the incident wave period.
4. Preliminary processing of the acquired displacements' measurements for Models 1 and 2 and preliminary computation of the rotations for Model 2 indicate that there is need for considering shorter waves in order to experience resonant conditions.
5. Extensive analysis of the collected data is now in progress. The results of this analysis will be used for the enhancement and validation of the FENM developed by members of the User's Group party.

3 MAIN LEARNING OUTCOMES

3.1 Progress Made

3.1.1 Progress Made: For This User-Group or Technology

The collected data are required for the validation and enhancement of a FENM applying in beam structural elements undergoing LATR recently developed by members of the User Group.

3.1.2 Progress Made: For Marine Renewable Energy Industry

In the future, the enhanced and validated FENM is possible to be applied into existing numerical tools allowing a more refined and integrated analysis of fixed OWTs and, especially of floating OWTs.

3.2 Key Lessons Learned

The optimal vertical position of the physical model undergoing LATR can be achieved by combining: (a) effective reduce of the damping effect and (b) avoidance of the tested model's rising out of the water.

4 FURTHER INFORMATION

4.1 SCIENTIFIC PUBLICATIONS

The results of present research project will be disseminated through one publication in refereed international conference proceedings, which will include the experimental results of the present research project along with numerical results obtained from the FENM that has been recently developed by the present User Group as mentioned previously.

4.2 WEBSITE & SOCIAL MEDIA

Website: http://www.labima.unifi.it/CMpro-v-p-18.html
YouTube Link(s): http://www.youtube.com/user/coastlab/videos
LinkedIn/Twitter/Facebook Links:
Online Photographs Link: http://www.labima.unifi.it/CMpro-v-p-18.html

5 REFERENCES

Hsieh S-R., Shaw S.W., and Pierre C., 1994. "*Normal modes for large amplitude vibration of a cantilever beam*". International Journal of Solids and Structures, Volume 31, Issue 14, pp. 1981-2014.
Su Y., Ma C., 2012. "*Transient wave analysis of a cantilever Timoshenko beam subjected to impact loading by Laplace transform and normal mode methods*", International Journal of Solids and Structures, Volume 49, Issue 9, pp. 1158-1176.
Wang Z., Hong M., Xu J. and Cui H., 2014. "*Analytical and Experimental Study of Free Vibration of Beams Carrying Multiple Masses and Springs*", Journal of Marine Science and Application, Volume 13, Issue 1, pp. 32-40.
Muliawan M. J., Karimirad M. and Moan, T., 2013. "*Dynamic response and power performance of a combined Spar-type floating wind turbine and coaxial floating wave energy converter*", Renewable Energy, Volume 50, pp. 47-57.

6 APPENDICES

6.1 STAGE DEVELOPMENT SUMMARY TABLE

The table following offers an overview of the test programmes recommended by IEA-OES for each Technology Readiness Level. This is only offered as a guide and is in no way extensive of the full test programme that should be committed to at each TRL.

DEVELOPMENT PROTOCOL	STAGE 1 CONCEPT VALIDATION			STAGE 2 DESIGN VALIDATION	STAGE 3 SYSTEMS VALIDATION		STAGE 4 DEVICE VALIDATION		STAGE 5 ECONOMICS VALIDATION
	TRL 1: Confirmation of Operation	**TRL 2: Performance Convergence**	**TRL 3: Device Optimisation**	**TRL 4: Sub-Systems Assessment**	**TRL5: Sub-Assembly Bench Tests**	**TRL 6: Full System Sea Trials**	**TRL 7: Solo, Sheltered, Grid Emulator**	**TRL 8: Solo, Exposed, Grid Connected**	**TRL 9: Multi-device Array (3-5)**
Objectives/ Investigations	Op. Verification Design Variables Physical Process Validate/Calibrate Maths Model Damping Effect Signal Phase	Real Generic Seas Design variables Damping PTO Natural Periods Power Absorption Wave to Devise Response Phase	Hull Geometry Components Configurations Power Take-Off Characteristics Design Eng. (Naval Architects)	Final Design Accurate PTO [Active Control] Mooring system Survival Options Power Production Added mass	PTO Method Options & Control Inst. Power Absorption Electricity Production & Quality	Scale effects of Overall Performance Characteristics Mooring & Anchorage Security Environmental Influences & Factors	Oper & Mains Procedures Electrical Output Quality Grid Supply, Stability & Security PTO Performance at all phases Control Strategy Seaworthiness, Survival & Lifecycle Analysis Device Array Interaction (Stages 1 & 2)		Grid Connection Array Interaction Maintenance Service Schedules Component Life Economics
Output/ Measurement	Vessel Motion Response Amplitude Operators & Stability Pressure / Force, Velocity RAOs with Phase Diagrams Power Conversion Characteristic Time Histories Hull Seaworthiness; Excessive Rotations or Submergence Water Surface Elevation Abeam of Devices			Motion RAOs Phase Diagrams Power v Time Wave Climates @ *head, beam, follow*	PTO Forces & Power Conversion Control Strategies	Incident Wave Field 6 D of F Body Motion & Phase Seaworthiness of Hull & Mooring [Survival Strategies]	Full On-Board Monitoring Kit for Extended Physical Parameters Power Matrix Supply forecasting	Array Interaction Annual Power Prod. Elec. Power Perfm. Failure Rates Grid EIA reviews	Service, Maintenance & Production Monitor, Telemetry for Periodic checks & Evaluation
Primary Scale (λ)	$\lambda = 1 : 25 - 100$ ($\therefore \lambda_c = 1 : 5 - 10$)			$\lambda = 1 : 10 - 25$	$\lambda = 1 : 2 - 10$		$\lambda = 1 : 1 - 2$		$\lambda = 1{:}1$, Full size
Facility	2D Flume or 3D Basin			3D Basin	Power Electronics Lab	Benign Site	Sheltered Full Scale Site	Exposed Full Scale Site	Open Location
Duration *–inc Analysis*	1-3months	1-3months	1 3 months	6 – 12 months	6 – 18 months		12 – 36 months		1 – 5 years
Typical No. Tests	250 - 750	250 - 500	100 - 250	100 - 250	50 - 250		Continuous		Statistical Sample
Budget (€,000)	1 – 5	25-75	25-50	50 - 250	1,000 – 2,500		10,000 – 20,000		2,500 – 7,500
Device	Idealised with Quick Change Options Simulated PTO (0-∞ Damping Range) Std Mooring & Mass Distribution		Distributed Mass Minimal Drag Design Dynamics	Final design (internal view) Mooring Layout	Advanced PTO Simulation Special Materials	Full Fabrication True PTO & Elec Generator	Grid Control Electronics or Emulator Emergency Response Strategies Pre-Production	Pre-Commercial	Operational Multi-Device
Excitation / Waves	Monochromatic Linear (10-25Δf) (25-100 waves)	Panchromatic Waves (20min scale) +ve 15 Classical Seaways Spectra Long crested Head Seas		Deployment -Pilot Site Sea Spectra Long, Short Crested Classical Seas Select Mean wave Approach Angle		Extended Test Period to Ensure all Seaways inc.	Full Scatter Diagram for initial Evaluation Continuous Thereafter Time & Frequency Domain Analysis		
Specials	DofF (heave only) 2-Dimentional Solo & Multi Hull	Short Crest Seas Angled Waves As Required	Storm Seas (3hr) Finite Regular As required	Power Take-Off Bench Test PTO & Generator	Device Output Repeatability Survival Forces	Salt Corrosion Marine Growth Permissions	Grid Emulator Quick Release Cable Service Ops	Stakeholder Consult. Health & Safety Issues	Small Array (Up-grade to Generating Station)?
Maths Methods (Computer)	Hydrodynamic, Numerical Frequency Domain to Solve the Model Undamped Linear Equations of Motion		Finite Waves Applied Damping Multi Freq Inputs	Time Domain Response Model & Control Strategy Naval Architects Design Codes for Hull, Mooring & Anchorage System. Economic & Business Plan			Economic Model Electrical Stab. Array Interaction	Grid Simulation Wave forecasting	Array Interaction Market Projection for Devise Sales
	EVALUATION [Stage Gates]								
Absorbed / Converted Power [kW]									
Weight, [tonnes]									
Manufacturing Cost [€]									
Capture [kW/tonne] or [kW/m^3]	[200-50 m^3]								
Production [c/kW]	< 25 €c / kW			≤ 15 €c / kW			≤ 10 €c / kW		≤ 5 €c / kW

6.2 Any Other Appendices