Experimental assessment of the effect of water depth on mooring line tensions for two different WEC mooring configurations under solitary waves

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I. INTRODUCTION

To this date a wide variety of technologies able to convert potential and kinetic wave energy into electric energy, has been proposed [1,2,3,4]. According to their deployment location, wave energy converters (WECs) can be classified as onshore, nearshore and offshore devices. Onshore devices are installed at the shore and often integrated in civil infrastructure. In the case of nearshore devices, these are installed at moderate water depths (h), typically up to 40 meters, and can be moored systems or directly fixed to the seabed. On the other hand, offshore devices are moored devices deployed in water depths typically over 40 meters.

Water depth is strongly related to the cost of electricity production of the technology. Because of the influence of the seabed, the energy density near to the shoreline decreases. Deploying such devices far from the coast implies access to sites with higher wave power, increasing energy production [5]. Furthermore, nearshore waves tend to be unidirectional, they are oriented towards the coast, whereas offshore waves have multiple directions [6]. These wave characteristics makes it challenging to harness energy from offshore locations. Moreover, the higher the distance from the coast and deeper waters, implies higher capital expenditure (CAPEX) related to mooring systems and electrical infrastructure. In addition, offshore devices must be designed to withstand higher loads from operational and extreme sea states. Additionally, this feature affects operational expenditure (OPEX) since a greater distance from the coast transfer into a more expensive installation, operation, maintenance, and dismantling.

A critical aspect to evaluate in wave energy projects is the capacity to survive extreme events. These events are mainly caused by weather conditions which expose devices to extreme sea states and non-linear loads such as breaking wave impacts. The extreme loads exerted on the devices, which are much higher than operational loads, place special demands on the mooring and Power take off (PTO) systems, increasing the possibility of damage and, therefore, generating higher repair costs [7].

Although nearshore WECs are less exposed to extreme events caused by weather conditions, the risk related to the exposure to another type of extreme events, such as tsunamis increases [8]. Thus, the evaluation of this aspect is critical on countries with high tsunami occurrence rates such as Chile, Japan, and the United States. Since nonlinear effects arise as tsunami waves approach the coast [9], it is crucial to study their interaction with structures by numeric and physical models. However, the physical simulation of these waves is a complex task due to large space and time scales [10]. Therefore, it is a common practice to approximate such waves by other long wave which are simpler to generate, such as solitary and N-waves [11]. In addition to a first approximation to the problem, the use of this type of waves can be used to validate numerical models which then allows the simulation of closer to real tsunami conditions.

II. METHODS

In the present work, an experimental approach is followed to evaluate loads exerted by solitary waves over two generic WEC models. Simulations were performed in the Wave and Towing Tank of Universidad Austral de Chile. This tank is 45 [m] long, 3 [m] wide and 2 [m] high. At one end of the tank there is a paddle-type wave generator which has 2 operation modes: flap and piston. In piston mode it is possible to generate long waves, considering a maximum stroke of 0.58 [m].

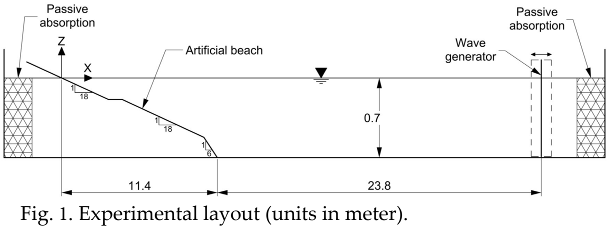

Fig. 1. Experimental layout (units in meter).

TABLE I
MODEL INSTALLATION POSITIONS

Position	x [m]	h [m]	h_{FS} [m]	h/h_{max}
P1	12.417	0.700	52.50	1
P2	9.460	0.467	34.88	0.66
P3	8.447	0.413	30.53	0.58
P4	7.452	0.359	26.25	0.50

FS subindex means Full Scale value

Maximum height (H) for solitary waves was defined in 6 [m] in full scale, considering the condition of the 1730 Cartagena Bay tsunami as reference, which is the highest registered tsunami event at the Chilean central coast [12]. Then, in order to study different tsunami magnitudes, intermediate wave heights of 2 [m] and 4 [m] were defined. Also, the water depth at the generation zone (h_{max}) was defined as 52.5 [m]. Considering the above, a scale factor of 75 was selected. In order to simulate a simplified shore, an artificial 11.4 [m] long beach was deployed on the opposite side of the wave generator, Fig.1. Then, four installation positions for the models were defined: one of them in uniform water depth 1 [m] before the beginning of the beach and 3 other positions over the artificial beach, TABLE I.

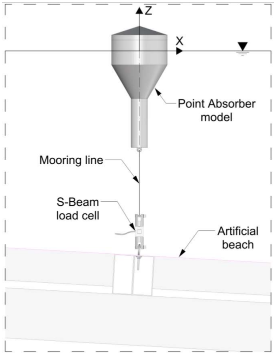

Fig. 2. Vertical mooring configuration.

Generic models represent different Point absorber WECs. Aiming to evaluate the influence of mooring configuration on the load magnitude over mooring lines, these models share the same geometry and differ on their mooring configuration. One of them uses a vertical mooring configuration, as used on one-body devices (e.g., CorPower) and the other one considers a horizontal mooring configuration, as employed on two-body Point absorbers (e.g. PB3 PowerBuoy). In order to avoid restoring forces exerted by the mooring system, a material with low axial stiffness was used in each mooring line. Then, mooring line tension was measured at the four different installation positions. Also, videos of all tests were recorded.

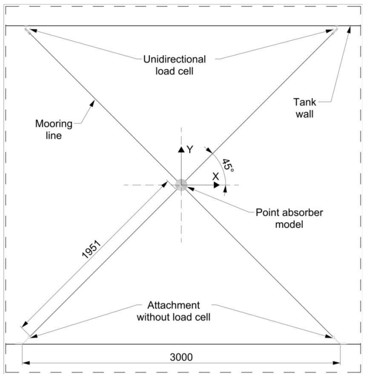

Fig. 3. Horizontal mooring configuration (units in millimeters).

III. RESULTS

The three solitary wave signals (H1, H2 and H3) generated were measured at position P1 without considering the presence of models, Fig. 4. All these waves comply with shallow water condition (h/L under 0.05). Moreover, measured wave profiles differ from theory in amplitude, being smaller in the experiments, Table II. Also, signals present a trough below mean water level after reaching their maximum amplitude, which does not agree with theory.

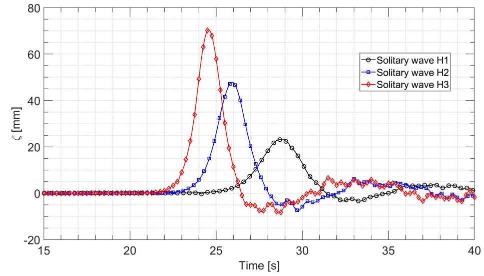

Fig. 4. Solitary wave signals at P1.

Mooring line tension exerted by waves over the vertical moored Point absorber follows a behaviour similar to the wave amplitude, increasing until reaching its maximum value and then decreasing to a value below the pretension, Fig. 5. Although peak force increases with wave height, the effect of water depth is insignificant. Thus, maximum mooring line tension variation was 4.21 [N] approximately, which was recorded with solitary wave H3. Then, the models reserved buoyancy related to their non submerged part is equivalent to 3.68 [N]. This water level is almost reached in solitary wave H2. Then, if this force is considered, just 0.53 [N] of the maximum mooring line tension variation (4.21 [N]) corresponds to dynamic forces induced by particle velocities.

TABLE II
TESTED SOLITARY WAVES

Solitary wave	H [m]	H_{FS} [m]	H/h	h/L
H1	0.026	1.5	0.029	0.023
H2	0.053	3.3	0.063	0.035
H3	0.080	5.1	0.097	0.043

FS subindex means Full Scale value

Nevertheless, when the horizontal force exerted by waves over the horizontal moored Point absorber model is analysed, a clear influence of depth in the magnitude of this force can be observed. Thus, the maximum measured horizontal force variation was 1.21 [N] at position P4 with the highest wave height.

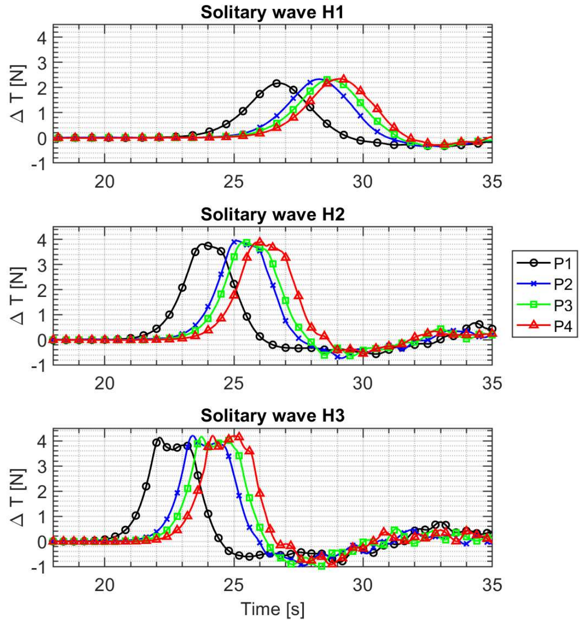

Fig. 4. Variation of mooring line tension of vertical moored Point Absorber model.

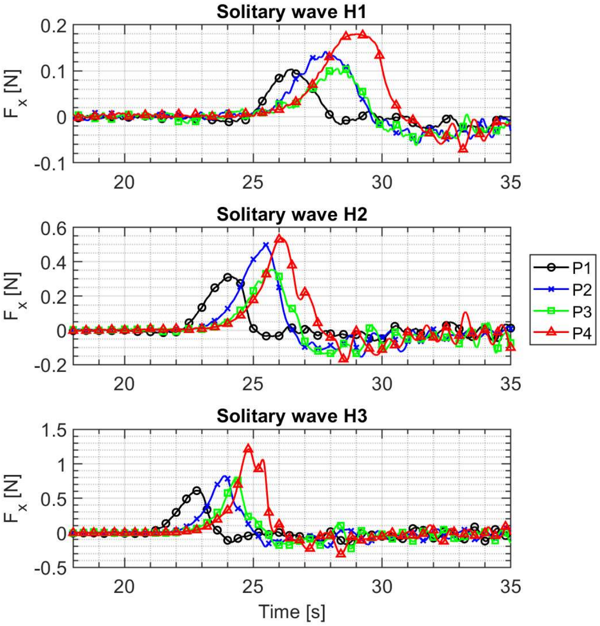

Fig. 5. Variation of horizontal force exerted by mooring system of horizontal moored Point absorber model.

IV. DISCUSSION & CONCLUSION

Both models have different degrees of freedom due to their mooring configurations, Fig. 6. On the vertical moored Point absorber, vertical motion is restricted and can only orbit with respect to the fixed point of its mooring line. Meanwhile, in the horizontal moored Point absorber model, horizontal motion is more restricted, while motion on the vertical direction is allowed. In this way, as water level locally increases when solitary waves travels, the horizontal moored WEC moves with it, following the waves, whereas the vertical moored WEC tends to partially submerge under the wave, increasing its displaced volume. Therefore, if we consider that the designer considers the complete sinking of the device under a tsunami wave, the dynamic forces can be significantly decreased for the vertical moored WEC, when compared with the horizontal mooring layout.

In the case of the horizontal moored WEC, it can be observed that water depth has a major effect on wave loads. Thus, F_x doubles its magnitude in solitary wave H3 as water depth is reduced by half. However, this value does not increase at the same ratio in other waves, where the increment was equivalent to a 75.4% and 73.3% in solitary waves H1 and H2, respectively. Meanwhile, the mooring line force barely increased 2% for the vertical moored WEC, which is negligible compared to the horizontal moored WEC. This difference shows that the increase in horizontal velocity of the water column with decreasing depth is significantly greater than the increase in vertical particle velocity.

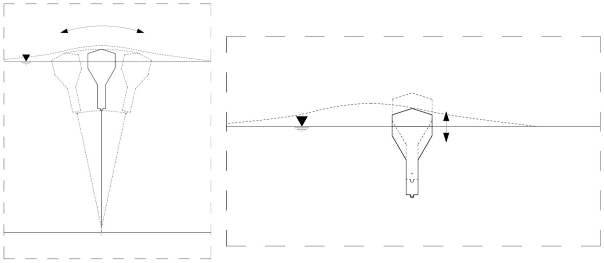

Fig. 6. Degrees of freedom of vertical (left) and horizontal (right) moored Point absorber models.

These results suggest that such WECs using a vertical taut line mooring configuration have advantages when deployed at intermediate or shallow waters when considering survivability under solitary waves, as dynamic forces remain almost constant as water depth is reduced. This feature goes together with the advantage of these devices to operate at low depths in terms of PTO efficiency [12]. Moreover, although horizontal force increases significantly with depth reduction in horizontal moored WECs, it must be considered that in these tests the mooring system restricts its horizontal motion and does not provide restoring capacity, thus this factor can play a crucial role on dynamics. Additionally, the influence of device geometry must be studied to further clarify these statements.

Finally, in order to evaluate the survivability of these devices under tsunami waves, the hydrodynamic response of these closer to real conditions must be studied, particularly wave profiles and bathymetry, for which these results might be used to validate numerical models.

V. ACKNOWLEDGEMENTS

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