Submerged horizontal plate used for wave energy extraction and as a potential coastal defence alternative

Manuel G. Verduzco-Zapata, Francisco J. Ocampo-Torres, Ramòn O. Jiménez-Betancourt, and Ernesto Torres-Orozco

Abstract—**A submerged horizontal plate breakwater provides shelter by inducing wave breaking, generation of vortex and interference with the incoming waves due to the presence of a reverse pulsating flow formed below the plate. This pulse may also be used as a source for energy extraction. Three prototypes (1/50 scale) with different plate geometries were tested to evaluate their efficiency to generate the under current: a) a solid plate (*SP*); b) a plate with an inner rectangular void with a Venturi tube type in the central section (*VTP*); and c) a plate with an inner rectangular void with a positive sloped section at the bottom of the rear end of the plate (*PSP*). The vertical dimension of the inner void and the submergence and length of the plate were varied. The numerical model *FLOW-3D* was used to simulate different wave scenarios using Second Order Stokes Waves with two different slopes, propagating in intermediate waters. The results showed that the three types of plates gave a pulsating flow. The *VTP* and the *PSP* gave strongest currents, but the former had its maximum in the positive x-direction (parallel to the direction of the wave propagation), whereas the latter had it in the opposite direction. From the three plate types, the *PSP* placed at d_s/h = 0.18 had the lowest transmission of wave energy downstream, suitable to be used as a coastal protection structure.**

Keywords— **Flow-3D model, Horizontal plate, wave energy converter, wave-structure interaction.**

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M. G. Verduzco-Zapata is with the Faculty of Marine Science, University of Colima Carretera Manzanillo-Cihuatlán km 19.5 Colonia El Naranjo. C.P. 28868, Manzanillo, Colima, México (e-mail: manuel_verduzco@ucol.mx).

F. J. Ocampo-Torres is with the Department of Physical Oceanography, CICESE, Carretera Ensenada-Tijuana 3918, Ensenada, Baja California, México (e-mail: ocampo@cicese.mx).

R. O. Jimenez-Betancourt is with the Faculty of Electro-mechanic Engineering, University of Colima, Carretera Manzanillo-Cihuatlán km 19.5 Colonia El Naranjo. C.P. 28868, Manzanillo, Colima, México (e-mail: rjimenez@ucol.mx).

E. Torres-Orozco is with the Faculty of Marine Science, University of Colima Carretera Manzanillo-Cihuatlán km 19.5 Colonia El Naranjo. C.P. 28868, Manzanillo, Colima, México (e-mail: etorres@ucol.mx).

I. Introduction

As an alternative to conventional submerged breakwaters, a horizontal plate can be designed to significantly dissipate wave energy[1], providing shelter for marine activities. Nevertheless, such structures can be expensive then the interest to share costs with other sectors, such as the energy industry. A plate breakwater is a long, box type open breakwater[2] that produces several mechanisms for wave dissipation depending on its location in the water column: wave breaking, generation of vortex[3–5] and the interference with the orbital velocities of the incoming waves due to a reverse pulsating flow formed beneath the plate [6]. The last process has been previously studied to analyse its viability to be used as an alternative energy source to be harvested by a turbine. Using the Boundary Element Method (BEM) and linear potential theory, [7] measured the diffraction velocity potential around the plate and compared the results with experimental data. It was found that placing the plates too close to the surface could decrease the efficiency of the device as a WEC, as severe dissipation would occur due to wave breaking, and these processes need to be account by adequate turbulence models. Further experiments showed that the effect of nonlinearities is important on the current intensity [8]. On the other hand, [9] performed physical tests in a wave flume to study the flow around plates, focusing on the effect of changing wave period and wave heights in the generation of the undercurrent. Different structures below the plate were included in order to reduce the hydraulic area. Such geometries were a) a triangular structure with five different heights; and b) a vertical wall with two different heights. The velocities were measured using *KENEK* and *Vm-801 H-Type* electromagnetical meter. It was found that the best setup was the triangular form to increase the efficiency of the plate for wave energy harvesting. Similar numerical experiments were conducted by [10], concluding that an increase in height and period of waves interacting with plates of a given length produces a more intense undercurrent, considering different opening areas beneath the plate and submergence depths.

Another technique to quantify the undercurrent is by means of PIV methods. For instance, [3] performed an experimental study by means of this method and the results were compared with those obtained with *FLOW-3D* model, using different turbulence methods. It was concluded that the Large Eddy Simulation (*LES*) method is best for representing the vortex generation, followed by the *RNG* and the *k-ε* model. Based on this work, in the present research the *FLOW-3D* model was selected as a tool to study the wave-structure interaction. This approach is suitable for investigating the hydrodynamics around the Plate Wave Energy Converter (PWEC).

In the next section, the PWEC is described. Section III shows the experimental parameters used in the experiments. Section IV describes the numerical setup, including the equations employed, mesh properties and boundary conditions, as well as the instrumentation setup and data analysis techniques. Section V shows and discusses the results. Finally, section VI mention some conclusions.

II. PLATE WAVE ENERGY CONVERTER

Three different prototypes (1/50 scale) were tested to estimate the intensity of the currents generated under the plates. The first prototype consisted on a solid plate (SP) with a thickness of 0.02 m, and two different lengths (*B*) of 0.40 and 0.80 m. The second prototype consisted on a plate with an inner rectangular void with a Venturi tube type in the central section (VTP). The same two different lengths were used. The vertical distance between the inner walls of the plate before the area reduction (*x*) was changed between the experiments (0.04 and 0.08 m). The borders of the plate had a thickness of 0.02 m. Finally, the third prototype consisted on a plate with the same two different lengths, with an inner rectangular void with a 30° positive sloped section of 0.20 m at the bottom of the rear end of the plate (PSP). The borders of the PSP had a thickness of 0.02 m. The general geometries of the SP, VTP and PSP prototypes are shown in Fig. 1.

III. EXPERIMENTAL MATRIX

The tests covered the interaction between the plates and Second Order Stokes Waves with two different wave slopes (0.03 and 0.05) propagating in intermediate waters. The plates were located in two different position within the water column: submerged at 18 and 20 % the water depth (*h*). The parameters used in the tests are summarized in the experimental matrix shown in Table I.

TABLE I
EXPERIMENTAL MATRIX USED FOR THE EXPERIMENTS

Symbol	Definition	Values
H/L	Wave slope	0.03, 0.05
B/L	Relative length	0.20, 0.40
x/h	Relative spacing	0.10, 0.20
d_s/H	Relative submergence	0.18, 0.30
Ptype	Prototype	SP, VTP, PSP
H	Wave height at inlet boundary	0.06, 0.10 m
L	Wavelength at inlet boundary	2.0 m
B	Plate length	0.40, 0.80 m
x	Vertical dimension of inner void	0.04, 0.08 m
d_s	Water column above the top of the plate	0.072, 0.12 m
h	Water depth	0.40 m

IV. NUMERICAL WAVE FLUME SETUP

A. Flow 3D model - equations

FLOW-3D version 11.2.6.03 is a *RANS* model that solves the continuity equation and the three dimensional equations of motion by finite difference schemes, using grids with rectangular cells with uniform and non-uniform sizes. It is based on the Volume of Fluid method (*VOF*) [11], a very wide use technique for solving the free surface. The turbulence can be estimated using three different models: Large Eddy Simulation (*LES*), *k-ε* and Renormalization Group (*RNG*) models. Based on the results of [3], the *LES* method is applied. In this method, the large turbulent structures are resolved directly by the computational grid approximating only the features that are too small to be resolved. Details are described in the FLOW-3D manual [12].

B. Domain and plate implementation

The numerical wave flume had a constant water depth *h* and height of 0.40 m and 0.60 m, respectively, and it is formed by two mesh blocks. Blocks I and II are 12 m and 43 m long, respectively. In the *SP* and *VTP* tests, Block 1 had a resolution with a $dx = dz = 1$ cm, having a total of 72,000 (1200 x 60 x 1) cells. In the y-direction (width of the flume) there was only one cell, then the problem to be solved was 2-D. Block II had a coarse mesh with a $dx = dz = 2$ cm, with a total of 64,500 (2150x30x1) cells. The cell size was chosen to have at least 6 cells per wave height, enough for representing well the water surface elevation [13]. In the *PSP* tests, Block 1 had a resolution with a $dx = dz = 0.5$ cm, having a total of 288,000 (2400 x 120 x 1) cells. Block II had a coarse mesh with a $dx = dz = 1$ cm, with a total of 258,000 (4300x60x1) cells. In this case, the decrease in the cell size was required since the Fractional Area/Volume Obstacle Representation (FAVOR [14]) method used for implementing the plates, is affected by the resolution of the computational grid (see Fig. 1).

a)

b)

c)

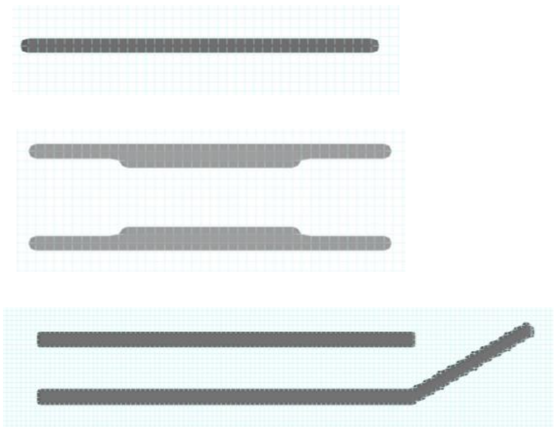

Fig. 1. Different PWECs representation (lateral view) using *FAVOR* method: a) *SP* (dx=dz=1 cm); b) *VTP* (dx=dz=1 cm); and c) *PSP* (dx=dz=0.5 cm).

Wave forcing was located at the inlet of Block I, whereas at the outlet boundary of block II a *Sommerfeld* radiation condition was defined to treat the open boundary. In addition, a numerical sponge with a length of 43 m was defined covering the entire length of Block II.

In the boundaries of the PWECs and at the bottom and lateral walls of the wave flume, the no-slip and impenetrability conditions were applied.

C. *Instrumentation*

A velocity sensor was beneath the plates at $B/2$. Three more sensors were located at a distance of 3.9, 3.7 and 3.4 m upstream of the plate to detect the water surface elevation in order to separate the incident from the reflected spectra using the method of [15]. The same method is used with another set of three sensors located at 3.4, 3.6 and 3.9 m downstream, to obtain the transmitted spectrum.

The time step (Δt) was set to 2x10^{-4} seconds. This small value was needed so the Courant stability condition was not exceeded during the experiments. The sample rate was set to 100 Hz.

V. RESULTS AND DISCUSSIONS

D. *Pilot tests*

The water surface elevations corresponding to the pilot test (without obstacles) and the Second Order Stokes wave theory are shown in Fig. 2 for comparison. The modelled wave heights H were 0.058 m and 0.095 m, *vs.* the targeted values of 0.06 m and 0.10 m, respectively. As it can be seen, the theoretical and numerical results are in good agreement.

a)

b)

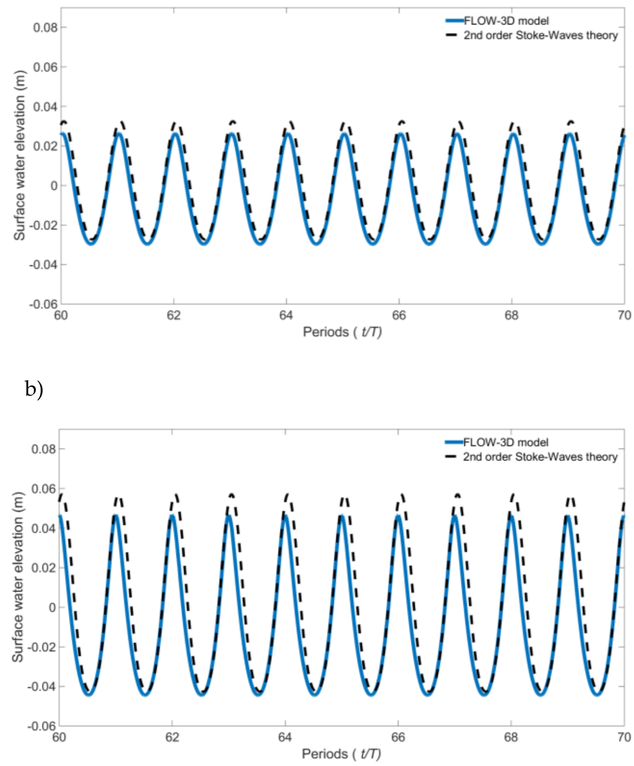

Fig. 2. Comparison between the water surface elevations calculated with *FLOW-3D* and the Second Order Stokes wave theory: tests with a) H/L = 0.03; and b) H/L = 0.05. The x-axis shows the number of wave periods elapsed since the start of the experiment (t is the time and T is the wave period).

E. *Intensity and direction of the currents*

The horizontal velocity component (u) was analysed from the time series obtained with the sensors located beneath the plates. The tests showed the presence of a pulsating current under the three different PWECs employed.

When the longest *SP* (B/L = 0.40) were located nearest to the water surface (d_s/h = 0.18) the flow reached higher magnitudes towards the negative x-direction (opposite to the direction of wave propagation). This is in accordance to the findings reported by [7,9,10]. On the other hand, when using the shortest *SP* (B/L = 0.20), u was mainly positive, regardless of the d_s/h value.

When placed at d_s/h = 0.18, the *VTP* produced an undercurrent mainly with positive values of u, whereas at d_s/h = 0.30 the *VTP* with an inner opening corresponding to x/h = 0.20, produced a balanced u in the positive and negative x-direction, with lower intensity than the current formed when using x/h = 0.10. The results suggest that decreasing x/h tends to increase the velocity magnitude. This is in agreement with the results obtained by [9,10] since they found that reducing the opening areas beneath the plate by means of submerged structures increase the intensity of the under current.

When the *PSP* was used, it produced an undercurrent mainly with negative values of u, with a slightly more intense magnitude when using x/h = 0.10.

In order to show the results, the cases with u velocities that exceeded a magnitude value of 0.15 ms^{-1} were selected (Fig. 3), and corresponded to the shortest plate (B/L = 0.20) interacting with the steepest waves (H/L = 0.05). The strongest current was obtained with the *VTP* placed at d_s/h=0.30, using an inner void with x/h = 0.10, with a mean, max, min, and standard deviation of 0.12 ms^{-1}, 0.34 ms^{-1}, -0.05 ms^{-1}, and 0.13 ms^{-1}, respectively.

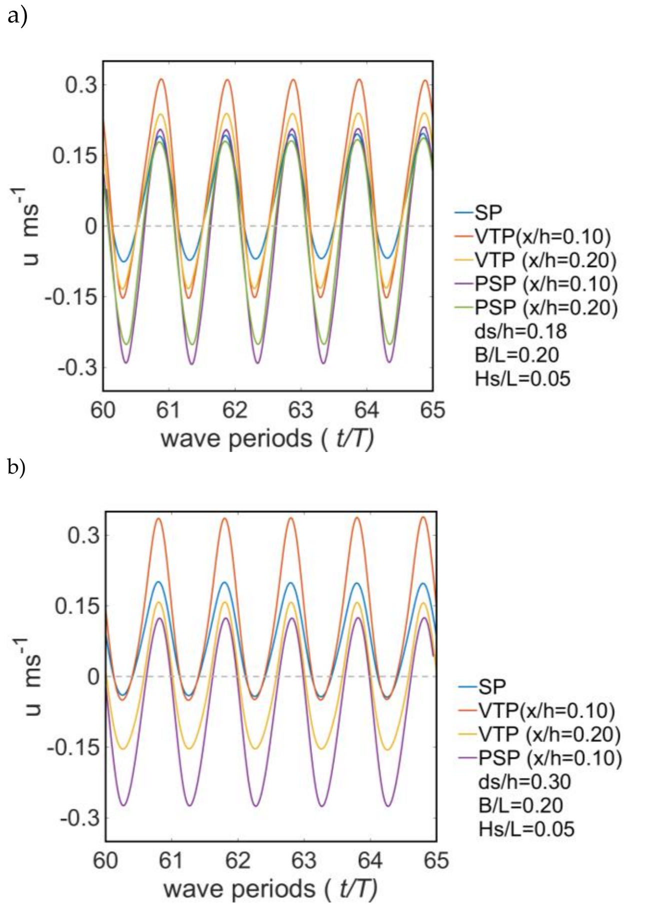

Fig. 3. Time series of the horizontal velocity component (u) measured below the different *PWECs*. From top to bottom: scenarios with d_s/h of a) 0.18; b) 0.30.

The results shows that the main direction of the flow beneath the plate could be downstream or upstream, depending on the PWEC employed and the parameters of the incoming waves. The pressure field evolution around the structures forces the changes in the u direction. For instance in Fig. 4, the case with *VTP* x/h = 0.10 and d_s/h = 0.30 had a strongest positive u (orange line in Fig. 3b) due to the pressure gradient that exist between the upstream and downstream ends of the PWEC.

On the other hand, the case with *PSP* (x/h = 0.10) and d_s/h = 0.30 had a strongest negative u (purple line in Fig. 3b) due to the pressure gradient that exists between the PWEC ends (Fig. 5). Note that Fig. 4 and Fig. 5 are cut in the vertical axis at a depth just below the PWECs for a clearer view of the pressure and velocity fields.

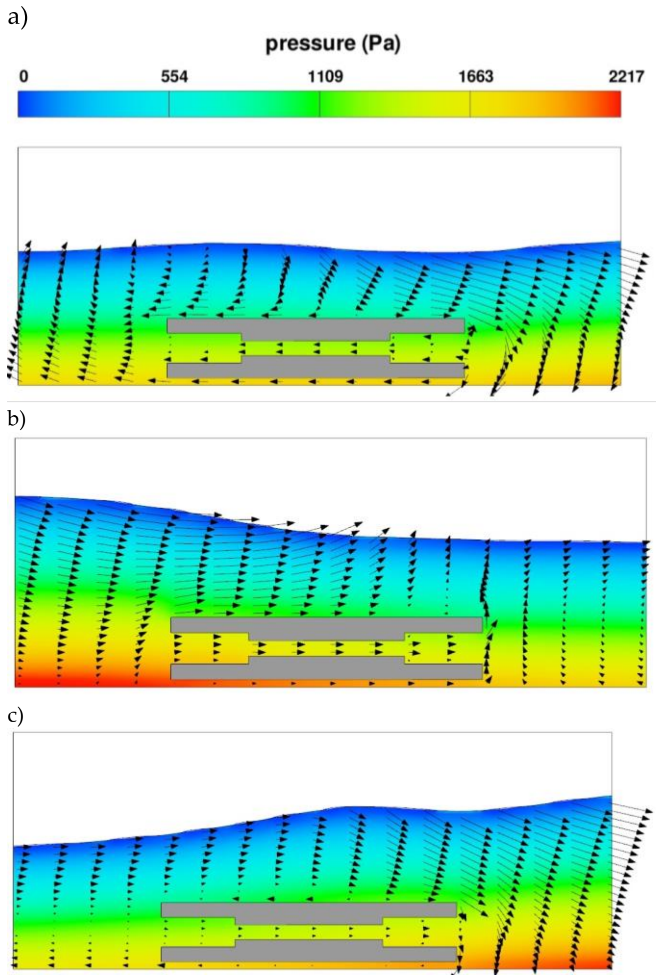

Fig. 4. Velocity and pressure fields induced by the *VTP* plate using the following non-dimensional parameters: d_s/h=0.30, B/L = 0.20, x/h=0.10 and H/L = 0.05. From top to bottom: screenshots at time: a) 60.26T, 60.67T and 61.07T (y and x axes are the vertical and horizontal elevations, respectively).

F. *Hydrodynamic coefficients*

The directional changes in the under current affect the efficiency of the PWEC to be used as a potential submerged coastal protection element. In this regards, [16] pointed out that plates could be used as an active wave attenuator due to the interference of the under current with the orbital velocities of the incoming waves. The transmission coefficients (k_t) of the nine cases presented in Fig. 3 were estimated using the three sensor method as proposed by [15].

The results are shown in Table II. It can be seen that the lowest k_t values were found in the tests where the PWECs are placed at d_s/h=0.18. In these experiments, the maximum u in the negative x-direction seems to decrease the value of k_t. For instance, the VTP with an inner void of x/h = 0.10, induced a higher negative u (-0.15 ms^{-1}) compared with the one with x/h = 0.20 (-0.13 ms^{-1}), having the former a smaller k_t value, 0.61 vs 0.63. In the PSP tests with an inner void of x/h = 0.10, a higher negative u (-0.29 ms^{-1}) was obtained compared with the one with x/h = 0.20 (-0.25 ms^{-1}), having the former a smaller k_t value, 0.54 vs 0.67.

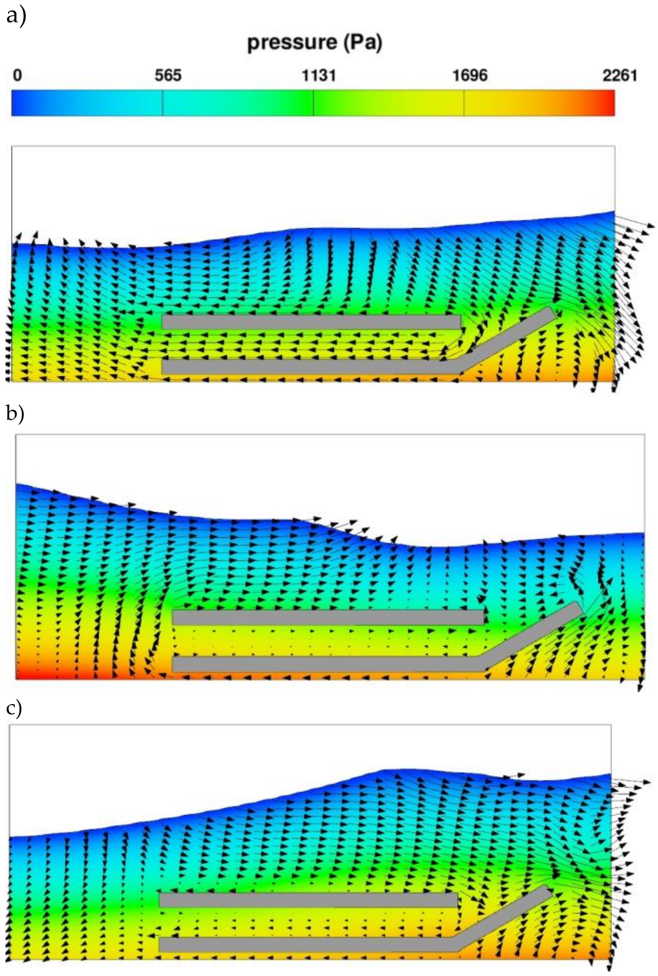

Fig. 5. Velocity and pressure fields induced by the *VTP* plate using the following non-dimensional parameters: d_s/h=0.30, B/L = 0.20, x/h=0.10 and H/L = 0.05. From top to bottom: screenshots at time: a) 60.26T, 60.67T and 61.07T (y and x axes are the vertical and horizontal elevations, respectively).

TABLE II
HYDRODYNAMIC COEFFICIENTS OF THE PWEC SELECTED

Ptype	H/L	B/L	x/h	d_s/h	k_t	$-u_{max}$
SP	*0.05*	*0.20*	*NA*	*0.18*	*0.71*	*-0.08*
SP	*0.05*	*0.20*	*NA*	*0.30*	*0.87*	*-0.04*
VTP	*0.05*	*0.20*	*0.10*	*0.18*	*0.61*	*-0.15*
VTP	*0.05*	*0.20*	*0.20*	*0.18*	*0.63*	*-0.13*
VTP	*0.05*	*0.20*	*0.10*	*0.30*	*0.87*	*-0.05*
VTP	*0.05*	*0.20*	*0.20*	*0.30*	*0.87*	*-0.16*
PSP	*0.05*	*0.20*	*0.10*	*0.18*	*0.54*	*-0.29*
PSP	*0.05*	*0.20*	*0.20*	*0.18*	*0.67*	*-0.25*
PSP	*0.05*	*0.20*	*0.10*	*0.30*	*0.82*	*-0.28*

VI. CONCLUSIONS

The numerical model *FLOW-3D* was used to simulate different wave scenarios using Second Order Stokes Waves with two different slopes, propagating in intermediate waters.

The results showed that the PWECs gave a pulsating flow. In contrast with the *VTP* and the *SP*, the *PSP* induced strong undercurrent flows mainly in the negative x-direction.

From the three plate types, the *VTP* had the strongest pulsating flow reaching a maximum of +0.34 ms^{-1}, when placed at d_s/h = 0.30, using an inner void with x/h = 0.10, making the *VTP*, followed by the *PSP*, the most suitable prototypes for harvesting the wave energy.

Considering the hydrodynamic coefficients obtained, the *PSP*, placed at d_s/h = 0.18, is the most appropriate to be used as a possible submerged coastal protection structure, which cost of construction and maintenance could be shared by Port and energy sectors.

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