Multidisciplinary Optimization of a Moored Rectangular Floating Breakwater

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ABSTRACT: The design optimization of floating breakwaters implicates solving a multidisciplinary problem consisting from three parts. The first one arises from the interaction of linear waves with a moored floating breakwater with a leeward boundary composed from a vertical wall. The second covers the dynamical behaviour of the structure; while the third concerns its structural mechanics. Next, the optimization problem is summarized by designing an optimal resistive breakwater with a minimum weight. The imposed constraints cover the floating condition, the stability, the maximum wave height in the port side, and the limitations for the mechanical stresses.

KEYWORDS: Floating breakwater; Wave modelling; Optimization; Structural resistance.

INTRODUCTION

Over the past two decades, interest in the study of the behaviour of floating breakwaters, FBWs, has increased owing to the requirement for the development of large number of new marinas and recreational harbours. The lower initial investment and the mobility of the structure of FBWs is attractive to the designer, where they are evaluated as a viable alternative when the cost of a fixed structure exceeds the economic return to be gained at that location and especially in sites with a large water depth and worse bottom foundation conditions.

As a result of all these positive effects, many types of floating breakwaters have been developed as described by McCartney (1985); however, the most commonly used type of floating breakwaters is the one that consists of rectangular pontoons connected to each other and moored to the sea bottom with cables or chains. Many studies have been directed towards the performance of floating breakwaters and its motion responses to understand their behaviour due to sea waves. For example, Drimer et al. (1992) presented a simplified analytical model for a floating rectangular breakwater in water of finite depth. Lee (1995) presented an analytical solution to the heave radiation problem of a rectangular structure, and he calculated the generated waves, added mass, damping coefficients and the hydrodynamic effect of the submergence, width of the structure. Hsu and Wu (1997) developed the boundary element method and applied it to study the heave and sway problem in a bounded domain (floating breakwater with a sidewall in the leeward side), which describes the real problem of breakwaters appearing in ports. Sannasiraj et al. (1998) adopted a two-dimensional finite element model to study the behaviour of pontoon-type floating breakwaters in beam waves, also Williams et al. (2000) investigated the hydrodynamic properties of a pair of long floating pontoon breakwaters of rectangular section. Lee and cho (2003) developed a numerical analysis using the element free Galerkin method and mainly concerning the influence of mooring line condition on the performance of FBWs. Shen et al (2004) studied the effects of the bottom sill or the topography change on the hydrodynamic and transmission coefficients by a semi analytical method. Gesraha (2006) investigated the reflection and transmission of incident waves interacting with long rectangular floating breakwater with two thin sideboards protruding vertically downward, having the shape of the Greek letter ∏.

Yet none of these studies have been discussing the structural design of floating breakwaters or more even optimizing its shape. On the other side, optimization of fixed breakwaters has been previously discussed by Ryu et al. (2005) but focused on minimizing the cost function imposed to structural failure constraints, and also by Castillo et al (2006) for composite breakwater types and similarly concerning the minimization of initial/construction costs subjected to yearly failure rate bounds for failure modes. Therefore, in this paper the study is directed towards optimization of floating breakwaters to reduce its weight, or to represent a new resistive form, in accordance to the physical and mechanical constraints.

The present paper represents a comprehensive study on the behaviour of a real pontoon-type floating breakwater appearing in ports; represented by floating structures oscillating on water surface of finite deep water and one side of the boundary with vertical sidewall. It is different to the problems of structures oscillation with unbounded domain, since a ship parked in the port is affected by the reflected waves by the vertical sidewall and also by the resonance bands occurring in this enclosed port region. It starts with a hydrodynamic modelling of the floating breakwater in order to be able to detect its performance and the water elevation in the port side. Then, it proceeds forward towards imposing an optimization problem to obtain a resistive form with a minimum weight, satisfying the relevant constraints outlined by: minimum wave height in the port, floating, stability, and mechanical resistance.

HYDRODYNAMIC MODELLLING OF FLOATING BREAKWATERS

Formulation of boundary value problem

Fluid is assumed to be ideal, flow is considered as irrotational, so we can apply a linear wave theory. The motions are assumed to be small, so that the body boundary conditions are satisfied very close to the equilibrium position of the body. A Cartesian coordinate system is used, with the origin at the mean free surface, *Oz* directed positive upwards and *Ox* directed positive in the direction of propagation of waves. The state of the fluid can be completely described by the velocity potential, $\phi(x,z,t) = \mathrm{Re}[\Phi(x,z)e^{-i\omega t}]$, where *Re* denotes the real part of the complex expression $i = \sqrt{-1}$ and t is the time. For the two-dimensional problem considered here, the time independent complex velocity potential $\Phi(x,z)$ satisfies the Laplace equation.

$$\nabla^2\Phi(x,z) = 0 \qquad (1)$$

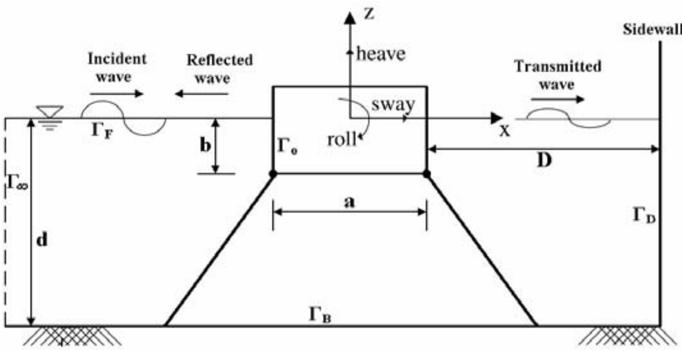

Fig.1 Definition sketch for theoretical analysis with a sidewall

The general configuration of an infinitely long floating structure interacting with a monochromatic linear wave of height, *H*, and wave angular frequency, $\omega = 2\pi/T$ is shown in Fig.1, where both the diffraction (waves incident on fixed structure) and radiation (structure oscillating in otherwise calm fluid) problems have been treated. It is generally convenient to separate the total velocity potential into incident potential, Φ_I, scattered potential, Φ_S, radiation potentials, Φ_j, j = 1, 2, 3 in three modes, heave, sway and roll.

$$\Phi(x,z) = \Phi_I + \Phi_S + \sum_{j=1}^{3}\Phi_j \qquad (2)$$

Where $\Phi_j = X'_j\varphi_j$ in which, φ_j is the radiation potential per unit body velocity, X'_j.

It is well known that the incident velocity potential of linear waves propagating from $x = -\infty$ to the positive direction is represented by:

$$\Phi_I = -\frac{igA}{\omega}\frac{\cosh[k(z+d)]}{\cosh(kd)}e^{ikx} \qquad (3)$$

where *g* is the gravitational acceleration, *d* is the water depth, *A* is the amplitude of wave and *k* is the wave number satisfying the dispersion relation :

$$\omega^2 = gk\tanh(kd) \qquad (4)$$

Diffraction problem

The boundary value problem for the diffracted potential (Φ_D) can be defined by the governing Laplace equation and the boundary conditions as defined below:

$$\Phi_D = \Phi_I + \Phi_S \qquad (5)$$

$$\nabla^2\Phi_D = 0 \qquad \text{in the fluid domain } \Omega \qquad (6)$$

$$\frac{\partial\Phi_D}{\partial z} - \frac{\omega^2}{g}\Phi_D = 0 \quad \text{at the free surface, } \Gamma_F,\ z = 0 \qquad (7)$$

$$\frac{\partial\Phi_D}{\partial z} = 0 \quad \text{at the sea bed, } \Gamma_B,\ z = -d \qquad (8)$$

$$\frac{\partial\Phi_D}{\partial z} + ik\Phi_D = 0 \quad \text{at the radiation boundary, } \Gamma_\infty,\ x \to -\infty \qquad (9)$$

The infinite boundary Γ_∞ is fixed at a finite distance, $x = x_R$. The position of the radiation boundary relative to the characteristic dimension of the structure and water depth is described in detail by Bai (1977). In the diffraction problem the rigid body is restrained from all its degrees of freedom, the kinematic boundary condition on the body can be expressed as follows:

$$\frac{\partial\Phi_D}{\partial z} = 0 \quad \text{on the body surface, } \Gamma_0,\ z = -b,\ -a/2 \le x \le a/2 \qquad (10)$$

$$\frac{\partial\Phi_D}{\partial x} = 0 \quad \text{on t he body surface, } \Gamma_0,\ x = \pm a/2,\ -b \le z \le 0 \qquad (11)$$

$$\frac{\partial\Phi_D}{\partial z} = ik\frac{k_r - 1}{k_r + 1}\Phi_D \quad \text{on the sidewall surface, } \Gamma_D,\ x = a/2 + D,\ -d \le z \le 0 \qquad (12)$$

where $k_r = 1$: corresponds to total reflective sidewall

$0 < k_r < 1$: corresponds to partial reflective sidewall

Radiation problem

The wave radiation problem can also be described by a radiated potential represented as

$$\Phi_j(x,z) = -i\omega X_j\varphi_j(x,z) \qquad (13)$$

The linear radiation boundary value problem is defined by the Laplace equation as a governing equation, and the boundary conditions are as given below

$$\nabla^2\varphi_j = 0 \qquad \text{in the fluid domain } \Omega \qquad (14)$$

$$\frac{\partial\varphi_j}{\partial z} - \frac{\omega^2}{g}\varphi_j = 0 \quad \text{at the free surface, } \Gamma_F,\ z = 0 \qquad (15)$$

$$\frac{\partial\varphi_j}{\partial z} = 0 \quad \text{at the sea bed, } \Gamma_B,\ z = -d \qquad (16)$$

$$\frac{\partial\varphi_j}{\partial z} + ik\varphi_j = 0 \quad \text{at the radiation boundary, } \Gamma_\infty,\ x \to -\infty \qquad (17)$$

For the radiation potentials, φ_j, $j = 1,2,3$, the kinematic body boundary condition or the body-fluid interface may be written as:

$$\frac{\partial \varphi_j}{\partial x} = ik\frac{k_r - 1}{k_r + 1}\varphi_j \text{ on the sidewall surface, } \Gamma_D, \; x = D + a/2 \qquad (18)$$

$$\frac{\partial \varphi_j}{\partial n} = n_j \qquad \text{on the body surface, } \Gamma_0 \qquad (19)$$

Where n_1 and n_2 are the x and z components of the unit inward normal to the body and $n_3 = (x - x_c)n_2 - (z - z_c)n_1$, in which (x_c, z_c) are the coordinates of the centre of rotation.

Hydrodynamic forces

The hydrodynamic pressure at any point in the fluid can be expressed in terms of the velocity potential as:

$$P(x,z,t) = -\rho\frac{\partial \phi}{\partial t} = i\omega\rho\phi \qquad (20)$$

Where ρ is mass density of fluid. The hydrodynamic forces can be determined by integrating the pressure over the wetted body surface Γ_0.

$$F_j(x,z,t) = i\omega\rho\int_{\Gamma_0}\phi n_j d\Gamma \qquad (21)$$

The hydrodynamic forces thus calculated can be separated into wave exciting forces governed by the diffraction problem and the hydrodynamic restoring forces governed by the radiation problem. The wave exciting forces, F_j^e due to the diffracted potential can be expressed as

$$F_j^e(x,z,t) = i\omega\rho\int_{\Gamma_0}(\phi_I + \phi_S)n_j d\Gamma \qquad (22)$$

Where $j = 1,2,3$ correspond to heave, sway, and roll modes respectively. Concerning the hydrodynamic restoring forces, F_j^h, they can be evaluated as:

$$F_j^h = \int i\omega\rho X_k^{'}\varphi_k n_j d\Gamma = -\mu_{jk}X_k^{"} - \lambda_{jk}X_k^{'} \qquad (23)$$

Where μ_{jk} is the added mass coefficient proportional to the body acceleration and λ_{jk} is the damping coefficient proportional to the body velocity. Then, μ_{jk} and λ_{jk} are evaluated from the real and imaginary parts of the complex radiation potential, respectively:

$$\mu_{jk} = \rho\,\mathrm{Re}[\int_{\Gamma_0}\varphi_k n_j d\Gamma] \qquad (24)$$

$$\lambda_{jk} = \rho\omega\,\mathrm{Im}[\int_{\Gamma_0}\varphi_k n_j d\Gamma] \qquad (25)$$

It is useful to apply the numerical models to solve the diffraction-radiation problem, since they have proven to be efficient tools to predict the sea keeping behaviour of floating breakwaters. The numerical model is based on the finite element method, and then all the integrals defining the hydrodynamic coefficients are also computed numerically.

Structural Dynamic Response

Although a floating body seems to have the same dynamic characteristics as a mechanic mass-spring system, there is an important difference that affects the dynamic behaviour. The water, surrounding the oscillating floating breakwater will determine the total mass and the damping of the system (Fig. 2). Since the magnitude of the so-called added mass and hydrodynamic damping parameters depend on the motion amplitude and frequency, these parameters are never constant. Therefore, the linear analysis procedure used to analyze the breakwater's motion is similar to the free vibration theory in air (Fig. 2). However, three new elements are introduced here. The motions are forced due to the waves passing over the structure, damping due to the fluid structure interaction is included, and the added mass term is included to account for the decreased response of the structure due to the presence of the external water. Then, the equation of motion, in matrix form, that describes the motion of the floating breakwater is given as:

$$[M + \mu]X^{"} + \lambda X^{'} + KX = F_j^e(t) \qquad (26)$$

Where the matrices of additional mass, μ, the damping matrix, λ, and the exciting forces, F_j^e, are determined from the previous parts. The resting terms or matrices M and K (body mass matrix and rigidity matrix) are derived from the Lagrange equations for the oscillating system considered in air and having three degrees of freedom. In the frequency domain, and due to the harmonic type of exciting forces $(F_j^e = f_j^e e^{-i\omega t})$, the response of the structure in waves can be found by:

$$[-\omega^2(M + \mu) - i\omega\lambda + K]\delta_j = f_j^e \qquad (27)$$

Where δ_j is the complex amplitude of the motion response, $X_j = \delta_j e^{-i\omega t}$.

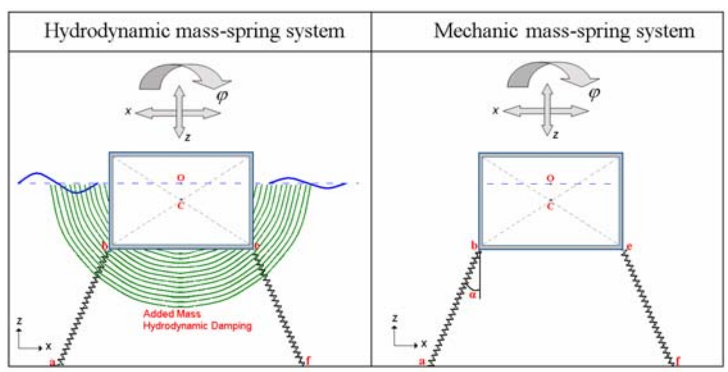

Fig.2 Representation of a hydrodynamic and a mechanic mass-spring system

The structural response will be analyzed by assuming that the breakwater behaves as a two dimensional rigid body undergoing small amplitude heave, surge and pitch motions. The Lagrange expression is:

$$L = \frac{1}{2}Mx_c^{'2} + \frac{1}{2}Mz_c^{'2} + \frac{1}{2}I\theta^{'2} + \frac{1}{2}k\left(\sqrt{(x_e - x_f)^2 + (z_e - z_f)^2} - l^2\right) + \frac{1}{2}k\left(\sqrt{(x_a - x_b)^2 + (z_z - z_b)^2} - l^2\right) \qquad (28)$$

Hence, the three equation of motion based on Lagrange equation can be expressed in terms of the three degrees of freedom (x_c, y_c, θ):

$$\frac{d}{dt}\left(\frac{\partial L}{\partial q'}\right) - \frac{\partial L}{\partial q} = 0 \qquad (29)$$

This formulation yields to nonlinear equations, which can be linearized by assuming small perturbations around the equilibrium positions.

$$x_c = x_{ceq} + x_{cnew} \quad , \qquad z_c = z_{ceq} + z_{cnew} \quad , \qquad \theta = \theta_{eq} + \theta_{new}$$

Finally, the equations of motions of the breakwater acted upon by the waves may be written as:

$$\begin{aligned} & Mx''_{cnew} + kx_{cnew}[2 + lG^{-3/2}r^2 - lG^{-1/2} + lH^{-3/2}u^2 - lH^{-1/2}] \\ & + kz_{cnew}[lG^{-3/2}rs + lH^{-3/2}uv] + k\theta_{new}[e_2 + lG^{-3/2}(e_2 r^2 - e_1 sr) \\ & - lG^{-1/2}e_2 + b_2 - lb_2 H^{-1/2} + lH^{-3/2}(b_2 u^2 - b_1 uv)] = 0 \end{aligned} \qquad (30)$$

$$\begin{aligned} & Mz''_{cnew} + kx_{cnew}[lG^{-3/2}rs + lH^{-3/2}uv] + lH^{-3/2}(b_2 uv - b_1 v^2)] \\ & + kz_{cnew}[2 + lG^{-3/2}s^2 + lG^{-1/2} + lH^{-3/2}v^2 + lH^{-1/2}] + \\ & k\theta_{new}[-e_1 + lG^{-3/2}(e_2 rs - e_1 s^2) + lG^{-1/2}e_1 - b_1 + lb_1 H^{-1/2} = 0 \end{aligned} \qquad (31)$$

$$\begin{aligned} & I\theta''_{new} + kx_{cnew}[e_2 + lG^{-3/2}\left(e_2 r^2 - e_1 rs\right) + lH^{-3/2}\left(b_2 u^2 - b_1 uv\right) + \\ & b_2 - le_2 G^{-1/2} - lb_2 H^{-1/2}] + kz_{cnew}[-e_1 + lG^{-3/2}\left(e_2 rs - e_1 s^2\right) + \\ & lH^{-3/2}\left(b_2 uv - b_1 v^2\right) - b_1 + le_1 G^{-1/2} + lb_1 H^{-1/2}] + \\ & k\theta_{new}[e_1^2 - e_2 s + lG^{-3/2}(e_e r - e_1 s)^2 - lG^{-1/2}(e_2^2 - e_1 r + e_1^2 - e_2 s) + \\ & b_1^2 - b_2 v + e_2^2 - e_1 r + b_2^2 - b_1 u + lH^{-3/2}(b_2 u - b_1 v)^2 - \\ & lH^{-1/2}(b_2^2 - b_1 u + b_1^2 - b_2 v)] = 0 \end{aligned} \qquad (32)$$

Where:

$$r = x_{ceq} + e_1 - f_1 , \qquad s = y_{ceq} + e_2 - f_2 , \qquad G = r^2 + s^2$$

$$H = u^2 + v^2 \; , \qquad u = x_{ceq} + b_1 - a_1 \qquad v = y_{ceq} + b_2 - a_2$$

And,

$$e(e_1, e_2) , \; f(f_1, f_2) \; , \; a(a_1, a_2) \; , \; b(b_1, b_2) \; , x_{ceq} = 0 , \; \theta_{eq} = 0$$

These three equations of motion are assembled in matrix form in order to directly substitute the elements of the K and M matrices in the principal equation (Eq.26). Now, the response amplitude can be directly derived from Eq.27, and the total velocity potential (Eq.2) can be simply calculated. Thus, the surface elevation for any point in the fluid domain can be derived by:

$$\eta(x,t) = \frac{i\omega}{g}\phi(x,z,t) \qquad (33)$$

OPTIMIZATION PROBLEM

A moored floating breakwater should be properly designed in order to ensure: (a) effective reduction of the transmitted energy, hence adequate protection of the area behind the floating system, (b) non-failure of the floating breakwater itself and (c) non-failure of the mooring lines. The satisfaction of these 3 requirements represents the overall desired performance of the floating breakwater. The reduction of the transmitted energy is achieved by satisfactory dimensions and mass of the floating structure itself, which are important parameters that can be used to optimize its performance. On the other side, the anchoring of the floating breakwater is necessary to keep the structure at the appropriate position. Besides the station keeping property, the mooring system is an important parameter that determines the dynamic behaviour of the mass-spring system. Moreover, for a breakwater to float it is obviously designed with a hollow form to reduce the total weight of the structure; where such form complicates the problem and implicates more constraints to be considered during the design.

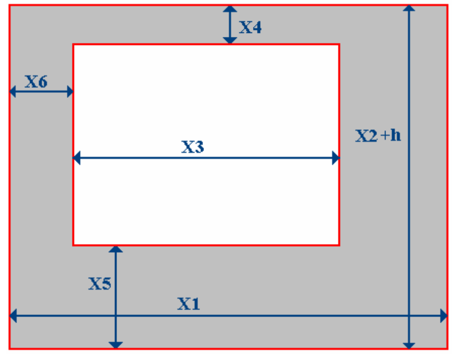

Fig.3 Defining the geometrical parameters of the floating breakwater

The usual shape optimization procedures start from the given initial design, where the boundary of the structure is described and parameterized using a set of simple segments such as straight lines, and then the shape is varied iteratively using the information from the shape design sensitivity to achieve finally the optimal shape design. Therefore, improving the performance of floating breakwaters could open up multiple of possible uses and this because the floating breakwater has many parameters characterizing its geometry (Fig.3) and defining its shape $x_i = [x_1, x_2, x_3, x_4, x_5, x_6]$. (The breakwater height above the calm water level (h) is taken to be a constant value equal to 2m). Some of these parameters are related to the same physical constraint where the rest are determined from other independent constraints. For example, any variation in the structural dimensions of the breakwater yields to changing the limiting boundary of the fluid domain. Therefore determining the geometrical dimensions cannot be performed as an ordinary calculation problem but it needs an optimization process in order to compute these parameters taking into consideration their influence on each other. The optimization problem is assumed to be finite dimensional constrained minimization problem, which is symbolically expressed as:

Find a design variable vector x_i ;

to minimize the weight function $f_{ob}(x_i)$

subjected to the ***n*** constraints $C_n(x_i) \le 0$

Objective function

The optimal solution is to design a breakwater respecting all the constraints with a minimum volume, hence the objective is to minimize the weight of the breakwater. It is expressed in terms of the geometrical dimensions as:

$$f_{ob}(x_1, x_2, x_3, x_4, x_5, x_6) = \rho_m \begin{bmatrix} (x_2 + h)x_1 \\ -x_3(x_2 + h - x_4 - x_5) \end{bmatrix} \qquad (34)$$

Floating constraint

It is obvious to mention that the floating breakwater must be designed with a hollow form to equilibrate the total weight of the breakwater with the submerged volume, where this yields to an important constraint relating the external dimensions to that of the hollow form. It is a direct application of Archimedes principle ($-\rho_m V_m g + \rho V_T g = 0$), where ρ_m and ρ designates the densities of the material (concrete) and the sea water respectively, V_m designates the volume of the inside material of the whole breakwater, where V_T designates the volume of the submerged part of the breakwater. In fact, for a moored structure the floating condition can be expressed in an inequality in order to minimize the weight, where the difference between the buoyancy force and the weight can be equilibrated by the tension in the mooring lines.

$$C_1 = -\rho_m V_m g + \rho V_T g \le 0$$

It is expressed in terms of the geometrical dimensions as follows:

$$C_1(x_1,x_2,x_3,x_4,x_5,x_6) = -x_1 \cdot x_2 + \frac{\rho_m}{\rho}\left[(x_2+h)x_1 - x_3(x_2+h-x_4-x_5)\right] < 0 \qquad (35)$$

Stability constraint

The initial horizontal equilibrium and the stability of the floating breakwater depend on the calculation of the centre of gravity. This is performed by dividing the breakwater into 4 rectangles and calculating the new position of the centre of gravity x_G (Fig. 4) in terms of the variables and then aligning it with the centre of buoyancy for the floating breakwater which lies at the geometric centre of volume of the displaced water $(x_1/2)$.

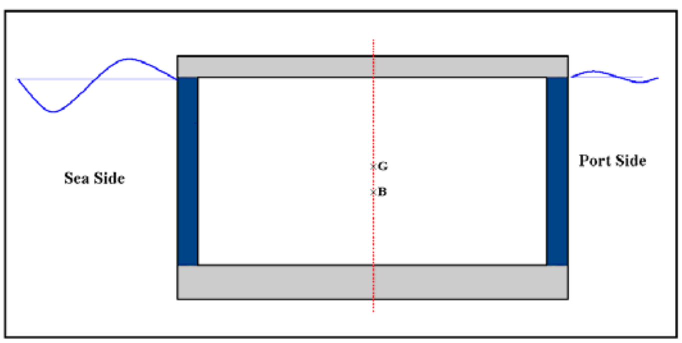

Fig.4 Centre of Gravity and centre of buoyancy

$$x_G = \frac{\begin{pmatrix} x_2+h \\ -x_4-x_5 \end{pmatrix}\left[\frac{(x_1-x_3-x_6)^2}{2} + \left(x_1 - \frac{x_6}{2}\right)x_6\right] + \frac{x_1^2}{2}[x_4+x_5]}{x_1 \times x_4 + x_1 \times x_5 + (x_2+h-x_4-x_5)(x_1-x_3)}$$

The horizontal equilibrium constraint is defined by

$$C_2(x_1,x_2,x_3,x_4,x_5,x_6) = x_G - \frac{x_1}{2} = 0 \qquad (36)$$

Minimum wave height in the port side

The floating breakwater will loose its efficiency when the wave conditions transmitted to the harbour area reach a maximum. This transmitted energy to the leeward side is mainly deduced from the underflow (wave energy not influenced by the floating breakwater presence) and the radiated waves created by the oscillating structure. This is the heaviest constraint in the optimization process, where the structural parameters and mainly the draft and width must vary in order to attenuate most of the incoming wave energy. Also these parameters must deviate the structure from resonance bands deduced from the clearance distance (distance between the breakwater and the reflective sidewall in the port) or from any coincidence between the structure natural frequency and the wave frequency. Hence, this demands a complete resolution of the hydrodynamic problem of the floating breakwater. The maximum wave allowable height in the port side is limited to 20cm and can be expressed as:

$$C_3(x_1,x_2,x_3,x_4,x_5,x_6) = \eta(x,t) - 0.2 < 0 \qquad \forall \; x > a/2 \qquad (37)$$

Structural constraints

This constraint constitutes a pure structural analysis of the floating breakwater, where a comprehensive numerical analysis based on the finite element method is requested in order to determine the mechanical stresses that must be restricted to certain limits. It can be summarized by maximizing the stiffness of the structure having a given shape. The floating breakwater is subjected to the hydrostatic forces on its sides and also the hydrodynamic forces exerted by the incoming waves, Eq.22. The forces in the anchoring system are also introduced, which equilibrates the difference between the weight and the pressure exerted on the bottom of the breakwater (Fig.5).

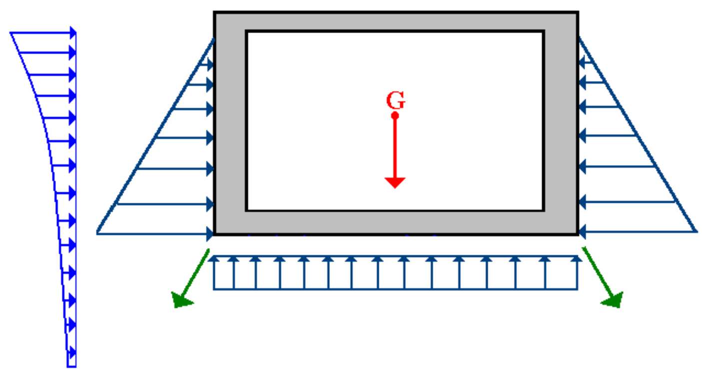

Fig.5 Floating breakwaters subjected to hydrostatic and hydrodynamic forces

It is well known that the concrete have different compression and traction limits due to its nature, and so the well known criteria of Von Mises for elastic materials cannot be used. A special criterion, named the Parabolic Criteria, (Garrigues.J, 2001) mainly used for concrete is introduced in terms of the principal stresses of the breakwater and the limit stresses for the material, and is written directly in the form of optimization constraint:

$$C_4(x_1,x_2,x_3,x_4,x_5,x_6) = (\sigma_1-\sigma_2)^2 - (\sigma_t+\sigma_c)(\sigma_1+\sigma_2) - \sigma_t\sigma_c \le 0 \qquad (38)$$

Where σ_1, σ_2 represent the principal stresses of the structure and σ_t, σ_c represent the limiting stresses for the material constituting the studied structure (hardened concrete: $\sigma_t = 6MPa$, $\sigma_c = -60MPa$). This constraint as the others must be computed in each iteration, which yields to solve the FEM problem in each iteration and for each new defined geometry in order to define the principal stresses.

APPLICATION and RESULTS

The essential characteristics of the waves, anchoring system and port characteristics are defined by the following:

$$\begin{cases} H = 2m \\ T = 9\sec \\ d = 40m \end{cases} \quad \begin{cases} k = 5\times10^{6}\ N/m \\ \alpha = 30^{\circ} \\ k_r = 0.3 \end{cases} \quad \begin{cases} D = 180m \\ \rho_m = 2300kg/m^3 \\ \rho_e = 1025kg/m3 \end{cases}$$

Using the Matlab optimization toolbox and mainly the function ***fmincon***; which is based on the SQP method (Sequential Quadratic Programming), the problem is solved to determine the structural variables $x_i = [x_1, x_2, x_3, x_4, x_5, x_6]$. This method is commonly referred to as Sequential Quadratic Programming method, since a quadratic subproblem (QP) is solved at each major iteration, where a nonlinearly constrained problem can often be solved in fewer iterations than an unconstrained problem using SQP.

The optimisation procedure above was applied for a floating breakwater constructed from concrete. The most important is the consistency between the hydrodynamic performance and the structural resistance of the breakwater. Thus, a floating breakwater meeting the structural requirements will have the best attenuating performance. For a significant wave (For example T=9sec, H$\geq$2m), it is difficult to design an optimal shape capable of totally attenuating the waves (allowable wave height=0.2) and respecting the resistance criteria at the same time. This reverts to the large width preferred by the hydrodynamic constraint and the inability of achieving resistive structure with such width especially when considering the floating constraint. This latter constraint plays an important role in resistance failure due to the small thickness given to the horizontal beams of the structure. Hence, we have two possibilities to surpass such a problem:

1- Designing a dual pontoon floating breakwater
2- Changing the material type

The first solution seems to be an interesting idea in the case of significant waves (Under the condition of taking into consideration the interaction between the two breakwaters in the fluid-structure model). A dual pontoon floating breakwater consisting of a pair of floating cylinders of rectangular sections connected by a rigid deck or totally separated, attenuates the waves on two stages (Fig.6). Thus, the concrete choice is still valid, and the optimization problem is reintroduced again but with a small variation in Eq. 37 which becomes: (maximum allowable wave elevation is 0.5 instead of 0.2)

$$C_3(x_1, x_2, x_3, x_4, x_5, x_6) = \eta(x,t) - 0.5 < 0$$

This yields to determine an optimal design of a concrete floating breakwater that is widespread utilized in moderate wave conditions and then introduces a second similar one to constitute the dual pontoon. The first one can totally protect the ports from normal waves or simply it can attenuate half of the significant waves. Thus, the remaining energy in such waves is totally arrested by the second stage of the dual floating breakwater.

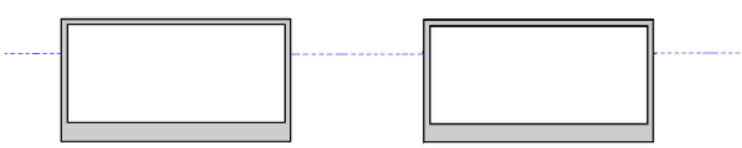

Fig 6 Dual pontoon floating breakwater

The numerical application for concrete and with a relatively high allowable wave height at the leeward side yields to the following results:

$$\begin{cases} x_1 = 11.95m & x_2 = 2.3m & x_3 = 11.35m \\ x_4 = 0.3m & x_5 = 0.3m & x_6 = 0.3m \end{cases}$$

Another possibility to overcome the failure of the resistance constraint with large width is to orient the interest towards a more effective and lighter material than the concrete. Then, it will be conceivable to design a single floating breakwater surviving with significant waves. This opens up a large choice between various types of materials. But, the accumulated experience proved that the employing of composite materials permit, with equal performance, a gain of mass varying from 10 % to 50 % over the same component in concrete, and with a cost of 10% to 20% less. Moreover, they are widely applied in the ocean field, mainly in hull ships superstructure construction, due to the demand for lighter materials to improve the floating condition and to ensure the mechanical resistance in structures. The following properties are given for a composite material fabricated from glass/epoxy:

Density $\rho = 1700\ Kg/m^3$

Elasticity Module $E = 12.4\times10^3\ MPa$

Tensile strength $\sigma = 90\ MPa$

The numerical application for composite materials that is capable of totally attenuating the waves in the port side yields to the following results:

$$\begin{cases} x_1 = 19.2m & x_2 = 2m & x_3 = 18.5m \\ x_4 = 0.35m & x_5 = 0.35m & x_6 = 0.35m \end{cases}$$

Through the optimization process of the two cases, we can clearly observe the priority for enlarging the width over the draft due to several advantages. When the structural width is increased, the mass will increase too. Also, a wide and heavy structure is hard to put into rotation or vertical oscillation. Moreover, a wide structure is not able to move along the relative short period waves. Therefore, the wider the structure, the longer the wave period on which the structure will resonate. Finally, the increase in the width will enlarge the hydrodynamic damping.

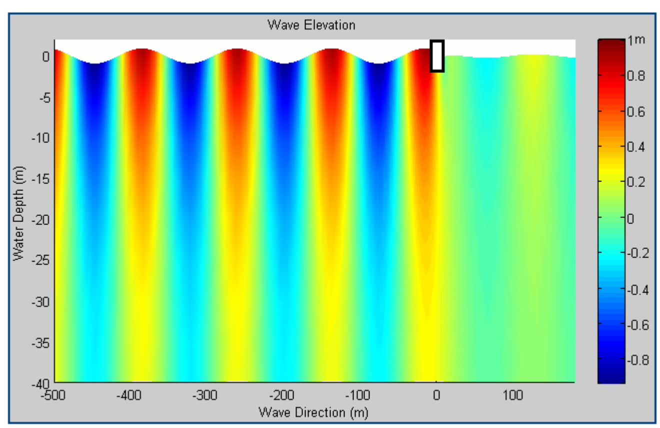

Fig.7 Wave elevation inside and outside (ocean) the port

Due to these facts, a wide structure is an effective solution to be applied in the case of ports influenced by waves with significant heights. In Fig. 7, a simulation of the wave propagation, in the same vertical plane of the performance of such structures. The fluid domain is taken from a 500m in the ocean side and 180m in the port side and with a water depth of -40m, where the floating breakwater constitutes a relatively small black rectangle with the white space representing its cavity. The diffraction of waves due to wide structure is more effective due to the increasing contact surface or the intersection domain of fluid-structure.

Then, almost a great part of the wave energy is being attenuated by the reflected waves. Also, the heave and roll radiations, due to the oscillation or dynamic behavior of the floating breakwater, are small due to cited reasons above. The last type of radiation caused by the sway motion maybe will be valuable in comparison with the other two, but it is playing a positive roll in attenuating totally the sea waves in the port domain. This horizontal oscillation of the breakwater is producing waves out of phase from the diffraction, heave and roll, thus yielding to a high protection of the port side (Fig 7). Therefore, it is easy to observe the small waves in the port side, which are under the allowable wave height value (0.2m). This also confirms the main purpose of floating breakwater which seeks to minimize the wave height in the port side in the contrary to the fixed breakwaters that are capable of completely annulling the waves.

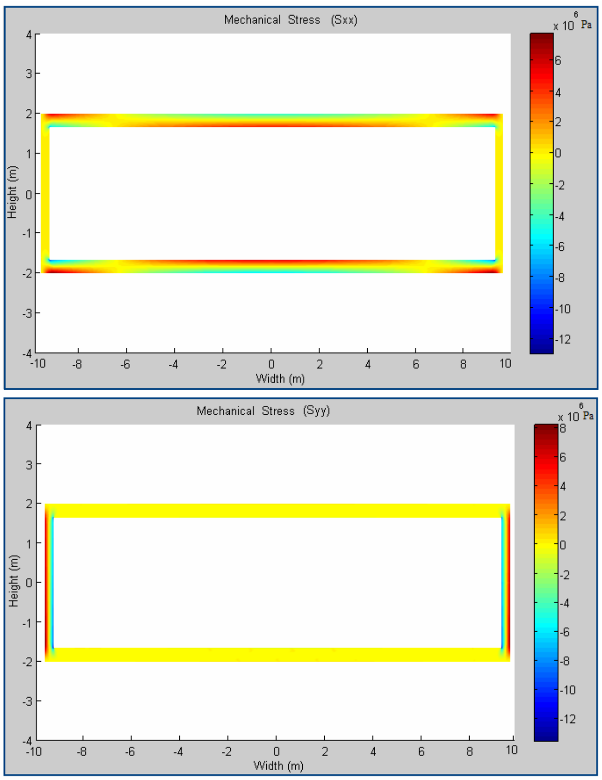

Fig. 8 Mechanical Stress Distribution for composite materials σ_x (left) σ_y (right)

Concerning the structure resistance, it is clear that the optimization iterations for the two types of materials are following the same methodology, which enlarges the width over the draft. The two problems yield to a similar design (enlarging width over draft with the remaining variables mainly not varying) and for two different wave height limitations inside the port (transmission coefficient=0.2 for composite and 0.5 for concrete). These results support or demonstrate the robustness of the problem methodology producing similar answers to two different problems. For the case of concrete, the resistance constraint failed to insure a width bigger than 12m; this is the main problem causing the incapability of designing a single concrete floating breakwater that can go forward toward a larger width and therefore a higher port protection. Where, we can figure out an analogous structure with a larger width computed for the composite materials. These materials have a large band to overpass the high mechanical constraints reverting from small thickness of the beams. The two horizontal beams (upper and lower) for the two materials are mainly subjected to bending stresses. The two deflections are opposite in sense and are oriented towards the core of the breakwater. The upper deflection is due to the weight of the material, while the lower one is resulting from the water pressure acting on the bottom. (Fig.8).

In fact, it is not only a problem of volume consuming, but also a structural advantage where the floating breakwater is working approximately in the same stress domain (Fig.8). This is an additional advantage for the floating breakwater, since the more the inside points are working on closer stresses values the more the extended life of the structure is expected and vice versa.

CONCLUSION

This work constitutes a theoretical background for floating breakwaters adaptable with the practical data and experience used in their construction that really still demands some physical and mechanical formulations. It is also an innovative study for real floating breakwaters appearing in ports. It constructed an optimization problem based on the hydrodynamic performance of the breakwater itself, and in relation with the resistance criteria and vibration for the floating structure. Moreover, this procedure must be applied to a vast frequency range to achieve the optimal floating breakwater that can sever in various environmental conditions. The importance of this study lies in its capability to present an optimal design for a floating breakwater depending on different wave characteristics or environmental conditions. Also, different materials can be tested to lately choose the optimal material type that can satisfy all the imposed constraints. Finally, this procedure can be applied not only on floating breakwaters, but also on many other offshore structures, floating bodies, and vehicles used in the ocean environment; where this cavity (empty space) can be benefited from it each case in its own domain.

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