HYDROELASTIC BEHAVIOR OF FLOATING FLEXIBLE PLATES ON SURFACE GRAVITY WAVES WITH THE EFFECTS OF VARIABLE BATHYMETRY

K. A. Belibassakis
School of Naval Architecture and Marine Engineering
National Technical University of Athens, Zografos 15710, Athens, Greece

G. A. Athanassoulis
School of Naval Architecture and Marine Engineering
National Technical University of Athens, Zografos 15710, Athens, Greece

1. SUMMARY

A coupled-mode technique is developed and applied to the hydroelastic analysis of flexible plates on surface gravity waves, modelling very large floating platforms of shallow draft lying over variable bathymetry regions. Under the assumption of small-amplitude incident waves and small deflections, the linearised equations have been used. In order to consistently treat the wave field beneath the elastic floating plate, the present approach is based on appropriate extensions of the coupled-mode model developed by Athanassoulis & Belibassakis [1] for waves propagating in variable bathymetry regions, which is free of any mild-slope assumption concerning the bottom boundary. Numerical results concerning floating structures lying over flat and sloping beds are presented, and the effects of the bottom slope on the hydroelastic responses of the system are discussed. An important feature of the present approach is that it can be further extended to include the effects of weak nonlinearity.

2. INTRODUCTION

Very Large Floating Structures (megafloats) and platforms of shallow draft have been intensively studied, being under consideration for use as floating airports and mobile offshore bases. In this case hydroelasticity plays a substantial role; a lot of information, as well as progress on this subject, is available in the special issues of Marine Structures [2] and J. of Fluids and Structures [3]. Although non-linear effects are of great importance, as, e.g., in the study of significant local slamming phenomena, still the solution of the linearised problem provides valuable information, serving also as the basis for the development of weakly non-linear theory. The linearised problem can be effectively treated in the frequency domain and many methods have been developed; see, e.g., Kashiwagi [4].

In most applications, the water depth is assumed to be constant, which is practically valid in the case when the horizontal dimensions of the floating structure are small in comparison to the bottom variation length or in the case of deep water. However, in cases involving the operation of large floating structures in the nearshore and/or coastal environment, the variations of bathymetry may have a significant effect; see, e.g. Shiraishi et al [5]. Numerical methods for predicting the hydroelastic responses of VLFS in variable bathymetry regions have been recently proposed, based on BEM in conjunction with fast multipole techniques [6], and on eigenfunction expansions in conjunction with a steplike bottom approximation [7]. In the present work, a coupled-mode technique is developed and applied to the hydroelastic analysis of very large floating platforms of shallow draft lying over variable bathymetry regions. Under the assumption of small-amplitude incident waves and small elastic deflections, the linearised wave equations have been used and the shallow-draft platform has been modelled as a thin elastic plate.

In order to consistently treat the wave field beneath the elastic floating structure down to the sloping bottom boundary, the present approach is based on appropriate extensions of the coupled-mode model developed by Athanassoulis & Belibassakis [1] and extended to 3D by Belibassakis et al [8], for waves propagating in
variable bathymetry regions. This model is free of any mild-slope assumption concerning the bottom. The present method is derived by an unconstrained variational principle, in conjunction with a rapidly-convergent local-mode series expansion of the wave field in the finite subregion, containing the elastic plate and the bottom irregularity, leading to an equivalent coupled-mode system of equations and appropriate end conditions. The latter ensure the matching of the wave field, and the requirement that the edges of the platform are free of moment and shear force. Thus, the problem is conveniently treated, for all scales concerning the width of the plate and the geometry of the strip with respect to the incident wavelength. Numerical results are presented concerning the responses of thin elastic plates lying over flat and sloping beds, illustrating the effects of bottom slope and curvature on the hydroelastic characteristics of large floating platforms.

3. DIFFERENTIAL FORMULATION

The studied environment consists of a water layer bounded above by the free surface and below by a rigid bottom; see Fig. 1. It is assumed that the bottom surface exhibits an arbitrary one-dimensional variation in a subdomain of finite length, i.e. the bathymetry \( h(x) \) is characterised by straight and parallel bottom contours lying between two regions of constant but possibly different depth: \( h = h_i \) (region of incidence) and \( h = h_f \) (region of transmission). A Cartesian coordinate system is introduced, with its origin at some point on the mean water level (in the variable bathymetry region), the \( z \)-axis pointing upwards and the \( y \)-axis being parallel to the bottom contours. The function \( h(x) \) appearing in the above definitions, represents the local depth, measured from the mean water level. It is considered to be a twice continuously differentiable function, such that \( h(x) = h(a) = h_i \), for all \( x \leq a \), and \( h(x) = h(b) = h_f \), for all \( x \geq b \); see Fig.1.

We consider the scattering problem of monochromatic, obliquely-incident, surface (gravity) plane waves of angular frequency \( \omega \), under the combined effects of variable bathymetry and a semi-infinite, thin, floating elastic plate extending from \( x = a \) to \( x = b \). The waves propagate with directions \( \theta_1 \) and \( \theta_3 \) with respect to the \( x \)-axis in the regions of incidence \( (x \leq a) \) and transmission \( (x \geq b) \), respectively. Under the assumption of irrotationality, the problem can be treated by partial separation of variables with respect to the transverse \((y)\) coordinate, and is governed by the modified Helmholtz equation on the vertical \((xz)\) plane. In this case, the wave potential can be expressed in the form

\[
\Phi(x,y,t) = \text{Re} \left( -\frac{igH}{2\omega} \phi(x,z) \exp(i(qy-\omega t)) \right),
\]

where \( H \) is the incident wave height, \( g \) is the acceleration due to gravity, \( q = \kappa^{(1)}_n \sin \theta_1 \) is the periodicity constant along the \( y \)-direction and \( i = \sqrt{-1} \). The problem of water-wave scattering by the elastic plate, with the effects of variable bathymetry, can be formulated as a transmission problem in the bounded subdomain \( D^{(2)} = \{ -h < z < 0, a < x < b \} \), with the aid of the following general representations of the complex wave potential \( \phi(x,z) \) in the two semi-infinite strips \( D^{(1)} = \{ -h_i < z < 0, -\infty < x < a \} \) and \( D^{(3)} = \{ -h_f < z < 0, b < x < \infty \} \):

\[
\phi^{(1)}(x,z) = \left( A_i \exp(ik^{(1)}_n x) + A_x \exp(-ik^{(1)}_n x) \right) Z^{(1)}_n(z) + \sum_{n=1}^{\infty} C^{(1)}_n Z^{(1)}_n(z) \exp(k^{(1)}_n(x-a)), \quad \text{in } D^{(1)}, \tag{2a}
\]

\[
\phi^{(3)}(x,z) = A_i \exp(ik^{(3)}_n x) Z^{(3)}_n(z) + \sum_{n=1}^{\infty} C^{(3)}_n Z^{(3)}_n(z) \exp(k^{(3)}_n(b-x)), \quad \text{in } D^{(3)}, \tag{2b}
\]

In the series (2), the terms \( \left( A_i \exp(\kappa^{(1)}_n x) + A_x \exp(-\kappa^{(1)}_n x) \right) Z^{(1)}_n(z) \) and \( A_i \exp(\kappa^{(3)}_n x) Z^{(3)}_n(z) \) are the propagating modes, while the remaining ones \((n = 1,2,\ldots)\) are the evanescent modes. In the above expansions, \( A_x \) and \( A_i \) denote the reflection and transmission coefficients, and \( k^{(1)}_n = \sqrt{(\kappa^{(1)}_n)^2 - q^2} \), \( k^{(3)}_n = \sqrt{(\kappa^{(3)}_n)^2 + q^2} \), \( n = 1,2,3,\ldots, \ i = 1,3 \), are horizontal wavenumbers, where \( \{ i \kappa^{(1)}_n, \kappa^{(3)}_n, n = 1,2,\ldots \} \), are obtained as the roots of the dispersion relations

\[
\mu h_i = -\kappa^{(1)}_n \tan \left( \kappa^{(1)}_n h_i \right), \quad \mu = \omega^2 / g, \quad i = 1,3. \tag{2c}
\]
The functions \( \{Z_n^{(i)}(z), n = 0, 1, 2, \ldots\} \) appearing in Eqs. (2a,b) are given by
\[
Z_n^{(i)}(z) = \frac{\cosh \left( \kappa_n^{(i)}(z + h) \right)}{\cosh \left( \kappa_n^{(i)} h \right)},
\]
\[
Z_n^{(i)}(z) = \frac{\cos \left( \kappa_n^{(i)}(z + h) \right)}{\cos \left( \kappa_n^{(i)} h \right)}, \quad n = 1, 2, \ldots, \quad i = 1, 3.
\] (2d)

Using the representations (2), the problem can be re-formulated as a transmission boundary value problem in the bounded subdomain \(-h(x) < z < 0\), \(a < x < b\), consisting of the following equations, boundary and matching conditions:
\[
(\nabla^2 - q^2) \phi^{(2)} = 0, \quad \text{in} \quad -h(x) < z < 0, \quad a < x < b, \tag{3a}
\]
\[
d \left( \frac{\partial^2 \phi^{(2)}}{\partial x^2} - q^2 \right) + (1 - \varepsilon) \frac{\partial \phi^{(2)}}{\partial z} - \mu \phi^{(2)} = 0, \quad \text{on} \quad z = 0, \quad \frac{\partial \phi^{(2)}}{\partial z} + \frac{d}{dx} \frac{\partial \phi^{(2)}}{\partial z} = 0, \quad \text{on} \quad z = -h(x), \tag{3b,c}
\]
\[
\phi^{(2)} = \phi^{(3)}, \quad \frac{\partial \phi^{(2)}}{\partial x} = \frac{\partial \phi^{(3)}}{\partial x}, \quad \text{at} \quad x = a, \tag{3d,e,f,g}
\]
\[
\frac{\partial^2 \phi^{(2)}}{\partial x^2} - (2 - v) q^2 \frac{\partial^2 \phi^{(2)}}{\partial x^2} \frac{\partial^2 \phi^{(2)}}{\partial z^2} = 0 \quad \text{and} \quad \frac{\partial^2 \phi^{(2)}}{\partial x^2} - v q^2 \frac{\partial^2 \phi^{(2)}}{\partial z^2} = 0, \quad \text{both at} \quad x = a, z = 0 \quad \text{and} \quad x = b, z = 0. \tag{3h,i,j,k}
\]

The boundary condition (3b), concerning \(\phi^{(2)}(x,z)\) on \(z=0\), describes the dynamics of the deflection \(w\) of the thin elastic plate, which is defined by (the kinematic relation):
\[
w(x,y) = \frac{i}{\omega} \frac{\partial \phi^{(2)}}{\partial z}(x,z=0) \exp(i q y). \tag{4}
\]

Eq. (3b) contains the (constant) parameters \(d = D/\rho g\), \(\varepsilon = \rho_0^2/\rho g\) and \(\mu = \omega^2/g\), where \(D=EI\) is the flexural rigidity, \(m\) is the mass per unit area of the plate, and \(\rho\) is the fluid density. Finally, the edge conditions (3h,i,j,k) state that the ends \((x=a\) and \(x=b\)) of the plate are free of shear force and moment, where \(v\) denotes the Poisson ratio.

**VARIATIONAL FORMULATION**

The problem (3) admits of an equivalent variational formulation, which can serve as the basis for the derivation of an equivalent coupled-mode system of equations on the horizontal plane. We consider a functional
\[
F \left( \phi^{(2)}, A_k; \{C^{(i)}_n\}_{n=1}^N, A_r; \{C^{(i)}_n\}_{n=1}^N \right),
\]
which is similar to the one presented in [1] with appropriate extra terms to account for the elastic-plate boundary condition (3b) and the end-conditions (3h,i,j,k). The function \(\phi^{(2)}(x,z), (x,z) \in D^{(2)}\) and the coefficients \(A_k; \{C^{(i)}_n\}_{n=1}^N\) and \(A_r; \{C^{(i)}_n\}_{n=1}^N\) constitute a solution of the problem, if and only if they render the functional \(F\) stationary, i.e. \(\delta F(\phi^{(2)}, A_k; \{C^{(i)}_n\}_{n=1}^N, A_r; \{C^{(i)}_n\}_{n=1}^N) = 0\).

Calculating the first variation \(\delta F\) of the above functional, making use of the Green’s theorem and the properties of the modal representations (2) in the semi-infinite strips \(D^{(i)}, D^{(i)}\), and applying twice integration by parts, the variational equation \((\delta F = 0)\) finally takes the form:
\[
\mu \int_{z=-h}^{z=0} \left( \nabla^2 - q^2 \right) \phi^{(2)} \delta \phi^{(2)} \, dz \, dx + \mu \int_{x=a}^{x=b} \left( \frac{\partial^2 \phi^{(2)}}{\partial x^2} + \frac{d}{dx} \frac{\partial \phi^{(2)}}{\partial z} \right) \delta \phi^{(2)} \, dx - \int_{x=a}^{x=b} \left( \frac{\partial^2 \phi^{(2)}}{\partial x^2} - q^2 \right) \frac{\partial \phi^{(2)}}{\partial z} \, dx + (1 - \varepsilon) \frac{\partial \phi^{(2)}}{\partial z} \left( \frac{\partial \phi^{(2)}}{\partial z} - \mu \phi^{(2)} \right) \delta \phi^{(2)} \, dx +
\]
\[
\mu \int_{z=-h}^{z=0} \left( \frac{\partial \phi^{(2)}}{\partial x} - \frac{\partial \phi^{(3)}}{\partial x} \right) \delta \phi^{(2)} \, dz - \mu \int_{z=-h}^{z=0} \left( \frac{\partial \phi^{(2)}}{\partial x} - \frac{\partial \phi^{(3)}}{\partial x} \right) \delta \phi^{(3)} \, dz - \mu \int_{z=-h}^{z=0} \left( \phi^{(2)} - \phi^{(3)} \right) \delta \phi^{(3)} \, dz + \mu \int_{z=-h}^{z=0} \left( \phi^{(2)} - \phi^{(3)} \right) \delta \phi^{(3)} \, dz +
\]
\[
\mu \int_{x=a}^{x=b} \left( \frac{\partial \phi^{(2)}}{\partial x} - \frac{\partial \phi^{(3)}}{\partial x} \right) \delta \phi^{(2)} \, dx - \mu \int_{x=a}^{x=b} \left( \frac{\partial \phi^{(2)}}{\partial x} - \frac{\partial \phi^{(3)}}{\partial x} \right) \delta \phi^{(3)} \, dx +
\]
\[
\mu \int_{z=-h}^{z=0} \left( \frac{\partial \phi^{(2)}}{\partial z} - \frac{\partial \phi^{(3)}}{\partial z} \right) \delta \phi^{(2)} \, dz - \mu \int_{z=-h}^{z=0} \left( \frac{\partial \phi^{(2)}}{\partial z} - \frac{\partial \phi^{(3)}}{\partial z} \right) \delta \phi^{(3)} \, dz = 0. \tag{5}
\]
THE LOCAL MODE REPRESENTATION AND THE COUPLED-MODE SYSTEM OF EQUATIONS

The problem (3) on $\varphi^{(3)}(x,z)$ in $D^{(3)}$ will be treated by an appropriate extension of the consistent coupled-mode theory, developed in [1], for water wave propagation in variable bathymetry regions. The following enhanced local-mode representation of the wave field (in the variable bathymetry region $D^{(3)}$ containing also the elastic plate) is introduced:

$$\varphi^{(3)}(x,z) = \varphi_{+1}(x)Z_{-1}(z;x) + \sum_{n=0}^{\infty} \varphi_n(x)Z_n(z;x), \quad \text{in } -h(x) < z < 0, \quad a < x < b. \quad (6)$$

In the above equation, the terms $\varphi_n(x)Z_n(z;x)$, $n = 0, 1, 2$, are the propagating modes and the remaining terms $\varphi_n(x)Z_n(z;x)$, $n = 3, 4, \ldots$ are the evanescent modes. The function $Z_n(z;x)$ represents the vertical structure of the $n$-th mode, and the function $\varphi_n(x)$ describing the horizontal pattern of the $n$-th mode is called the complex amplitude of the $n$-th mode. The functions $Z_n(z;x)$, $n \geq 0$, are obtained as the eigenfunctions of local vertical Steklov-type eigenvalue problems, formulated at each $x$ ($a \leq x \leq b$), and are given by

$$Z_n(z;x) = \frac{\cosh[k_n(x)(z + h(x))]}{\cosh[k_n(x)h(x)]}, \quad n = 0, 1, 2, 3, \ldots, \quad (7a)$$

where the eigenvalues $\{k_n(x)\}$ are obtained as the roots of the (local) dispersion relation

$$\mu = (d k^4(x) + 1 - \varepsilon)k(x) \tanh(k(x)h(x)), \quad a < x < b. \quad (7b)$$

Only the one-half symmetric subset of the roots of Eq. (7b) is used. Thus, $k_0$ is the real-positive root, $k_1$ is the root inside the first quadrant of the complex plane (i.e., $\text{Re}(k_1) > 0$, $\text{Im}(k_1) > 0$), $k_2$ is the conjugate-symmetric of $k_1$ (thus, $k_2 = -\text{Re}(k_1) + i \text{Im}(k_1)$), and $k_n$, $n = 3, 4, 5, \ldots$ are the roots lying on the positive-imaginary axis.

The additional term $\varphi_{+1}(x)Z_{-1}(z;x)$ is a correction term, called the sloping-bottom mode, which accounts for the bottom boundary condition on the sloping parts of the bottom. The idea behind this extra term lies in the fact that every finite truncation of the series (second part) in the rhs of Eq. (6), which is the usual local-mode series, is incompatible with the bottom boundary condition (3c) on the sloping parts ($h'(x) \neq 0$) of the bottom. This fact has the consequence that the series $\sum_{n=0}^{\infty} \varphi_n(x)Z_n(z;x)$ converges poorly, and a lot of terms have to be maintained in order to obtain accurate results. In contrast to the rest of the terms involving $Z_n(z;x)$, $n = 0, 1, 2, 3, \ldots$, which satisfy $\partial Z_n(z = -h(x);x)/\partial z = 0$ on the bottom, the term $\varphi_{+1}(x)Z_{-1}(z;x)$ is designed to satisfy the following conditions:

$$\frac{\partial Z_n(z = -h(x);x)}{\partial z} = 1, \quad d \frac{\partial Z_n(z = 0;x)}{\partial z^3} + (1 - \varepsilon) \frac{\partial Z_n(z = 0;x)}{\partial z} - \mu Z_n(z = 0;x) = 0. \quad (8a,b)$$

Eq. (8a) leads to a specific interpretation of the amplitude of the sloping-bottom mode:

$$\varphi_{+1}(x) = \frac{\partial \varphi^{(3)}(x,z = -h(x))}{\partial z},$$

which means that this term $\varphi_{+1}(x)Z_{-1}(z;x)$ identically vanishes on the horizontal parts ($h'(x) = 0$) of the bottom. Moreover, Eq. (8b) makes the sloping-bottom mode term compatible with the rest of the modes on $z = 0$. This in turn makes the whole set of modes, and thus the representation (6), compatible with both the bottom boundary condition (3c), as well as with the requirements of the boundary condition (3b) on $z = 0$, in conjunction with the Laplace equation (3a) in the vicinity of $z = 0$. An important effect of the extra term is that it makes the series (6) to converge remarkably faster, and thus, only a few evanescent modes have to be maintained in the series in order to obtain an accurate solution. A specific convenient form of $Z_{-1}(z;x)$ is given by $Z_{-1}(z;x) = h(x) \left[(z/h(x))^3 + (z/h(x))^2 \right]$, and all numerical results presented in this work are based on the above choice. However, other choices are also possible. For more details about the role and significance of the sloping-bottom mode see Ref. [1].
By introducing the local-mode series representation (6) in the variational principle (5), and by following exactly the same procedure as in [1], the following fourth-order coupled-mode system (CMS) is obtained (with respect to the amplitudes of the modes):

\[
\sum_{n=0}^{\infty} d_{mn}(x) \phi''_{n}(x) + b_{mn}(x) \phi'_{n}(x) + c_{mn}(x) \phi_{n}(x) + d_{mn}(x) \phi''_{n}(x) + e_{mn}(x) \phi'_{n}(x) = 0 , \tag{9}
\]

in \( a < x < b , \ m = -1,0,1,\ldots \), where a prime denotes differentiation with respect to \( x \). The coefficients of the system (9) are completely defined in terms of the local vertical basis \( \{Z_{n}(z;x)\} \) and the physical parameters of the problem. The above CMS is supplemented by the appropriate boundary conditions at the ends \( x = a \) and \( x = b \) (which are obtained from the variational equation), ensuring the matching of the wave field at the vertical interfaces. Also, from the last two terms of the variational equation (5) we obtain the appropriate edge conditions for the modal amplitudes \( \phi_{n}(x) \) at \( x = a \) and \( x = b \), ensuring that the elastic plate is free of shear force and moment, respectively, at the ends. Finally, the reflection and transmission coefficients \( (A_{R}, A_{T}) \) appearing in Eqs. (2) are obtained in terms of the solution of the CMS. An important feature of the solution of the problem by means of the enhanced representation (6), is that it exhibits an improved rate of decay of the modal amplitudes \( \phi_{n}(x) \) of the order \( O(n^{3}) \). Thus, a small number of modes suffices to obtain a convergent solution, even for large bottom slopes.

NUMERICAL RESULTS

The discrete version of the CMS is obtained by truncating the local-mode series (6) to a finite number \( N_{n} \geq 3 \) of terms (modes), and using central, second-order finite differences to approximate the horizontal derivatives. Discrete boundary conditions are obtained by using second-order forward and backward differences to approximate the horizontal derivatives appearing in the end-conditions, at \( x=a \) and \( x=b \). Thus, the discrete scheme obtained is uniformly of second order in the horizontal direction.

In order to illustrate the effects of variable bathymetry (sloping bottom) on the hydroelastic behaviour of the system, we examine the case of a thin elastic plate of width \( L=b-a=500m \) and flexural rigidity \( d=10^{5}m^{4} \), lying over a smooth underwater shoal, characterised by the following depth function

\[
h(x)=h_{0}+\frac{h_{1}-h_{0}}{2}\tanh\left(3\pi\frac{x-a}{b-a}-\frac{1}{2}\right), \quad a=0 < x < b = 500m . \tag{10}
\]

The average depth of this bottom profile, \( h_{av} = 0.5(h_{1}+h_{0}) \), has been taken equal to 10m. Numerical results obtained by the present method are presented in Fig. 2, for three bottom profiles generated by Eq. (10). The first one is a constant-depth environment characterised by \( h_{1}=h_{0}=10m \), the second is characterised by \( h_{1}=12m , \ h_{0}=8m \) and has maximum bottom slope \( s_{\max} = 3.8\% \), while the third one is much steeper, \( h_{1}=15m , \ h_{0}=5m , \ s_{\max} = 9.4\% \). The angular frequency of the incident wave has been taken to be \( \omega = 0.4 \) rad/sec, resulting in intermediate-to-shallow water wave conditions. The calculated reflection and transmission coefficients are: \( [A_{R}]=0.089, [A_{T}]=0.996 \), for the flat bottom case, \( [A_{R}]=0.10, [A_{T}]=1.082 \), for the 3.8% sloping bottom, and \( [A_{R}]=0.145, [A_{T}]=1.23 \), for the 9.4% sloping bottom. In Fig. 2 we present the effect of the bottom slope on the modulus of the elastic plate deflection \(|w/H|\). The three lines shown correspond to the three different bottom profiles. We observe in this figure that the elastic plate deflection significantly increases at the front (upwave) part \( (x/L < 0.5) \) of the plate. This result is due to the higher hydroelastic excitation by waves in this region, which is induced by the extra reflected energy from the shoal.

CONCLUSIONS

A consistent coupled-mode theory has been derived and applied to the hydroelastic analysis of very large floating platform of shallow draft lying over variable bathymetry regions. Under the assumption of small-amplitude incident waves and small elastic deflections, the linearised water-wave equations have been used, and
the shallow-draft platform has been modelled as a thin elastic plate. In order to consistently treat the wave field beneath the elastic floating structure, the present approach is based on appropriate extensions of the coupled-mode model [1], for waves propagating in variable bathymetry regions, which is free of any mild-slope assumption concerning the bottom boundary. The present method does not introduce any simplifying assumptions or other restrictions concerning either the bottom slope and curvature, or the vertical structure of the wave field. All wave phenomena are fully modelled and, thus, the present method can serve as a useful tool for the analysis of the hydroelastic behaviour of the system in the whole range of parameters within the regime of linear theory. Finally, the analytical structure of the present model facilitates its extension to fully 3D problems, as well as to the weakly non-linear (second and higher order) wave - elastic floating structure - seabed interactions in variable bathymetry regions.

Acknowledgements: This work was partially supported by the Section of Ship and Marine Hydrodynamics of National Technical University of Athens, in the framework of the project: “Wave Phenomena in the Sea and Coastal Environment”.

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