U.P.B. Sci. Bull., Series D, Vol. 72, Iss. 1, 2010 ISSN 1454-2358

LABORATORY RESEARCH ON MODELING OF THE ROMANIAN BLACK SEA SEASHORE WAVES INTERACTION WITH ENERGY CAPTURING DEVICES

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Lucrarea prezintă regimul valurilor pe litoralul românesc al Mării Negre, precum şi tehnologia utilizată pentru modelarea valurilor în condiţii de laborator. A fost de asemenea analizată şi descrisă în lucrare interacţiunea valurilor cu dispozitivele de captare a energiei valurilor, de tip angrenaj flotant. Prima parte a lucrării prezintă caracteristicile valurilor aferente litoralului românesc, bazate pe un program de măsurători pe termen lung, realizat de Departamentul de Meteorologie şi Hidrologie a Universităţii Bucureşti, punând în evidenţă frecvenţa de apariţie a valurilor în funcţie de înălţimea, frecvenţa şi perioada lor. A doua parte a lucrării tratează modul în care valurile de pe litoralul românesc, respectiv interacţiunea lor cu echipamentele de capturare a energiei, pot fi reproduse în canalul cu valuri al Laboratorului de Hidraulică de la Universitatea Tehnică de Construcţii Bucureşti, prin aplicarea criteriilor de similitudine.

The paper presents the wave regime of the Romanian Black Sea coastwise and also the used technology for the wave modeling in laboratory conditions. The wave interaction with the wave energy capturing devices, like the flotation gear type, was also analyzed and is described in this paper. The first part of the article presents the wave characteristics of the Romanian seashore area based on a long-term measurements program carried out within the Meteorology and Hydrology Department of the University of Bucharest by highlighting the frequency of wave occurrence based on their high, frequency and period. The second part of the paper deals with the way in which the Romanian seashore waves, as well as their interaction with the energy capturing equipment, can be replicate in the wave channel owned by the Hydraulics Laboratory, of the Technical University of Civil Engineering Bucharest, by applying the similitude criteria.

Keywords: Wave characteristics, wave modeling, wave energy capturing device

1. Introduction

In the past few years, analyzing the advantages of using the wave energy and considering the singularities of the Romanian Black Sea seashore, a particular interest is shifted towards the perspective of trapping and converting the wave

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energy. Therefore the determination of the wave characteristics of the Romanian Black Sea seashore based on a measurement program was a first aim carried out by the Meteorology and Hydrology Department experts of the University of Bucharest. A second aim of the research was to establish a way to replicate on scale models both the wave characteristics and the interaction between the wave field and the energy capturing devices. Thus, based on wave measurements, the determination of wave frequency occurrence on wave high and wave periods intervals was made for some characteristic sites of the Romanian seashore. Afterwards based on the similitude theory, the similitude criteria, the similitude conditions and the relation between the existing size scales used in developing the studied phenomenon were heightened throughout the "method of forces". Based on the similitude scales and on the parameters of the wave generator device the modeling procedure of the studied phenomena using the wave channel from the endowment of the Hydraulics Laboratory, Department of Hydraulics and Environmental Protection of the Technical University of Civil Engineering Bucharest (UTCB) was developed.

2. Wave characteristics of the Romanian Black Sea coastwise

In order to get familiar with the wave characteristics of the Romanian Black Sea coast in view of wave simulation to model (M), the wave characteristics were determined at a natural scale (N). The description of the corresponding wave regime for the analyzed area was made having as starting point a database regarding the wave heights $(H_v)_N$ and the wave periods $(T_v)_N$ determined for a 5 year interval. The main purpose was to calculate the f frequency of wave occurrence on intervals of height and period in Sfântu Gheorghe, Constanța and Mangalia tidewater points.

The determination of the frequency distribution (multiannual period percentage) for the wave appearance periods on height and period intervals for the three analyzed tidewater points has been considered of great interest for the determination of the parameters corresponding to the wave elements needed for the designing of wave energy capturing device. For this purpose, based on height and dominant period, frequency values, on intervals of height and dominant period, a wave statistical classification has been made, which was also graphically represented. An example, corresponding to Sfântu Gheorghe tidewater point, is shown in figure 1.

At Sfântu Gheorghe tidewater point this distribution shows two peaks. The first one is placed in the high range 0.25 ...0.50 m where the frequency value is 39.32% and the second one is placed in the range 0.75...1.00 m where the appearance frequency value is 15.96%. For Constanța tidewater point, the wave appearance frequency f distribution on wave high levels $(H_v)_N$ has a one-modal form presenting a strong right side asymmetry. This indicates that the range in which the peak distribution is situated is between 0.01...0.25 m, where the frequency value is 36.29%. The situation is different for Mangalia tidewater point in the sense that the height interval $(H_v)_N$ with a maximum wave appearance frequency f is 0.01...0.25 m, where the frequency value is 46.32%.

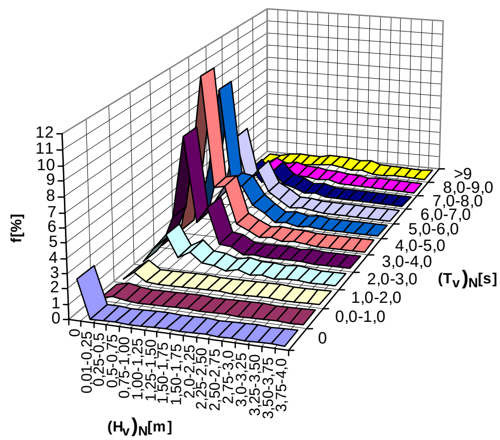

Fig. 1. The distribution of the appearance frequency f on wave height intervals $(H_v)_N$ and wave periods $(T_v)_N$ at Sfântu Gheorghe tidewater point

From the f frequency distribution analysis of wave occurrence on intervals of height $(H_v)_N$ and by summing the frequencies for all the period intervals a series of aspects could be distinguished. Based on the analysis of the wave appearance frequency f on period intervals $(T_v)_N$ and by adding the frequencies for all the wave height intervals it was observed that the highest frequency values are 25.13% for Sfântu Gheorghe station and 27.88% for Constanța station, placed in the interval 4...6 s. The situation is different at Mangalia station where, for wave periods values placed in the interval 5...7 s the wave appearance frequencies on period ranges are significant. These values are ranged from 26.90%, to 27.38%.

3. Laboratory modeling of the wave field and the energy capturing device flotation gear equipment interaction

In order to replicate the natural phenomenon from the prototype (N) at a reduced scale (M), on the model placed in the wave channel, it is necessary to determine the similitude criteria, the conditions of similitude and foremost the relation between the scales of magnitude that occur in the phenomenon development to be modeled ($S_x = x_M / x_N$). For this purpose the “method of forces" was used. To ensure the similitude between the (M) and (N) phenomena the tree forms of similitude, namely the geometrical, kinematical and dynamic similitude, must be achieved. The *geometrical similitude* supposes a single scale for wave length l_v, as well as for the energy capturing device flotation gear equipment characteristic lengths l_f ($S_{l_V} = S_{l_f}$), accordingly:

$$S_{H_v} = S_{Lv} = S_{H_f} , \tag{1}$$

were S_{H_v} , S_{Lv} and S_{H_f} are the wave height H_v, the wavelength L_v, and the floats vertical course H_f. The geometrical similitude can therefore be assured by carrying out the model as well as wave's incident component and the float gear, presenting no geometrical distortions, to a single scale of lengths.

The *kinematical similitude* between the model phenomena (M) and the prototype phenomena (N) achievement supposes the existence of the lengths and velocity scales ($S_{l_v} = S_{l_f}$ and $S_{U_v} = S_{U_f}$), constant for these kinds of experiments. Were S_{U_v} and S_{U_f} are the wave velocity scales U_v and the velocity specific for the float U_f (float's speed on the vertical direction movement). So:

$$S_{c_v} = S_{U_v} = S_{U_f} , \tag{2}$$

where S_{c_v} is the celerity scale. Thus, it results that the time scale S_t is a constant as well. For a periodical phenomenon, like the wave and the floats vertical movement, the time scale is also the period scale S_T of the similar phenomenon, same for the wave and also for the float.

The *dynamic similitude* of two phenomena (M) and (N) supposes a unique scale for the determinant forces of the studied phenomena, namely the wave forces of inertia F_{I_v} and the wave weight force F_{G_v}, for the wave modeling and for float's forces of inertia F_{I_f}, and the floats uplift force F_{A_f}, for modeling float's vertical movement under the wave action. From the force scales equality ($S_{F_{I,v}} = S_{F_{G,v}}$) and from the specific force scales for the waves:

$$S_{F_{I,v}} = S_{\rho_a} \cdot S_{l_v}^2 \cdot S_{U_v}^2 ,\ S_{F_{G,v}} = S_{\rho_a} \cdot S_{l_v}^3 \cdot S_g , \tag{3}$$

yields the relationship between the scales:

$$S_{U_v}^2 = S_{l_v} \cdot S_g \tag{4}$$

that leads to the similitude condition:

$$(Fr_V)_{\mathrm{M}} = (Fr_V)_{\mathrm{N}} \tag{5}$$

Therefore, for the wave movement the considered similitude criterion is Froude (Fr_v). From the force scales equality ($S_{F_{I,f}} = S_{F_{G,f}}, S_{F_{I,f}} = S_{F_{A,f}}$) and from the expressions of these scale forces specific to the float:

$$\begin{aligned} S_{F_{I,f}} &= S_{\rho_f} \cdot S_{l_f}^2 \cdot S_{U\,f}^2, \\ S_{F_{G,f}} &= S_{\rho_f} \cdot S_{l_f}^3 \cdot S_g, \\ S_{F_{A,f}} &= S_{\rho_a} \cdot S_{l_f}^3 \cdot S_g, \end{aligned} \tag{6}$$

yields the relations between the scales:

$$S_{U_f}^2 = S_{l_f} \cdot S_g;\; S_{U_f}^2 = S_{\rho_a} \cdot S_{\rho_f}^{-1} \cdot S_{l_f} \cdot S_g, \text{ or } S_{\rho_f} = S_{\rho_a} \tag{7}$$

where S_{ρ_a}, S_{ρ_f} and S_g are the water density, float material density and the gravitational acceleration scales.

Thus yields the conditions of similitude $(Fr_f)_{\mathrm{M}} = (Fr_f)_{\mathrm{N}}$ and

$$\frac{(\rho_f)_{\mathrm{M}}}{(\rho_f)_{\mathrm{N}}} = \frac{(\rho_a)_{\mathrm{M}}}{(\rho_a)_{\mathrm{N}}}, \tag{8}$$

where Fr_f is the Froude criterion referring to float's vertical movement. Taking into account that $S_g = 1, S_{U_v} = S_{c_v}$ and $S_{l_v} = S_{l_f}$, relations between scales are:

$$S_{c_v}^2 = S_{l_f},\; S_{U_f}^2 = S_{l_f},\; S_{\rho_f} = S_{\rho_a}. \tag{9}$$

In order to consider the scales of all the specific measures of this phenomenon, the fundamental scales and the derived scales expressed on the basis of the fundamental scales must be established. Thus, for the float model of the capturing device at the scale $S_{l_f} = (l_f)_M/(l_f)_N = 1/10 = 0.1$ and for the density scale in case of water $S_{\rho_a} = (\rho_a)_M/(\rho_a)_N = 1000/1011.5 = 0.0988$ the scales for the specific measures in case of the studied phenomenon are: $S_{H_v} = S_{L_v} = S_{H_f}$ =0,1, $S_{c_v} = S_{U_f}$ =0,316, S_{T_v} =3,16·10^{-1}, S_{ρ_f} =9,88·10^{-2}, $S_{G_f} = S_{A_f}$ =9,88·10^{-5}, $S_{E_v} = S_{E_c}$ =9,88·10^{-6}, $S_{P_v} = S_{P_c}$ =3,12·10^{-4}, where S_{E_v} , S_{E_c} are the wave energy scale, respectively the captured energy scale and S_{P_v} , S_{P_c} are the wave power scale respectively the captured power scale.

The wave field simulations were achieved in the wave channel owned by the Hydraulics Laboratory of UTCB, which is equipped for producing waves with different characteristic (wave generator), and has also the necessary measurement system. The wave generator (figure 2) is composed from a swing gate (mobile plane gate) jointed near the flume bottom (to a distance *a* = 0.05 m from the channel bottom) and actuated on the upper side, by a crank gear. The crank gear is driven by an electric engine with variable revolution, driven by a frequency converter.

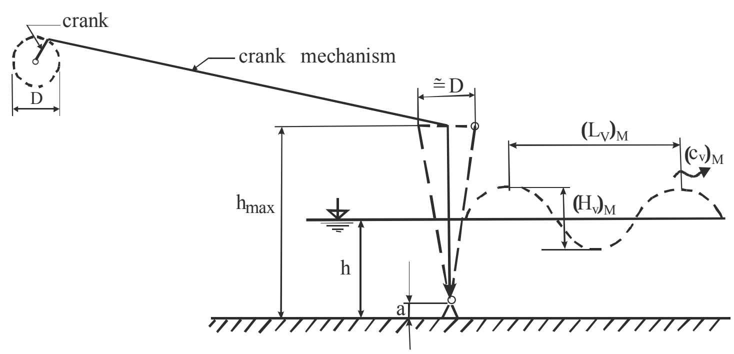

Fig.2. Simplified scheme of the wave generator that equips the wave channel owned by the Hydraulics Laboratory, Technical University of Civil Engineering Bucharest

The different values of the waves characteristics on the model (wave heights $(H_v)_M$, waves celerity $(c_v)_M$, wave lengths $(L_v)_M$, wave periods $(T_v)_M$) can be achieved by the cranks rev variation *n* as well as by modifying the cranks length that means also the change of the diameter *D*, which is approximately equal to the stroke of the upper and of the mobile gate positioned to the height h_{max}= 0.91 m from the channel bottom.

Thus, the generator is capable to produce waves whose characteristics can be modified continuously, covering the entire nature scale wave domain of the

Romanian coastal region replicate on the model by using the specific conditions of similitude.

For finding out the variation manner of the generator operation parameters (n, D) for a certain channel and a water depth h in order to obtain the different wave characteristics on model ($(H_v)_M$, $(c_v)_M$, $(L_v)_M$, $(T_v)_M$), the Hydraulics Laboratory experts, under the guidance of professor G. Tatu have accomplished a mathematical model specific to the aforementioned wave generator through which the wave characteristics depending on *n, D* and *h* were deduced as follows:

$$(T_V)_M = \frac{2\pi n}{60}; \tag{10}$$

$$(L_v)_M = (c_v)_M (T_v)_M; \tag{11}$$

$$(c_V)_M = \frac{g(T_V)_M}{(2\pi)\cdot \operatorname{th}\left\{\frac{2\pi h}{\left[(T_V)_M (c_V)_M\right]}\right\}}; \tag{12}$$

$$(H_V)_M = \frac{\pi D(h-a)}{(T_V)_M (c_V)_M (h_{max}-a)}, \tag{13}$$

where h_{max} = 0.91 m, and a = 0.05 m. Based on the above formulas, the characteristics of the generated wave were computed for a wide range of values of the wave generator. The obtained results were graphically represented and compared with the experimental tests results made in the wave channel. A very good correspondence of the two data types was observed.

4. Conclusions

For the Romanian Black Sea coastwise the wave appearance frequency f on wave height intervals $(H_v)_N$ reaches the maximum values on the interval 0.01…0.50 m, and those on wave period ranges $(T_v)_N$ reaches the maximum values on the interval 4.10…7.00 s.

The application of the "method of forces" leaded to the determination of the similitude criteria, similitude conditions and the relations between the considered measures size scales. These were useful to establish the wave characteristics corresponding to the Hydraulics Laboratory wave channel ($(H_v)_M$= 0…0.4 m and $(T_v)_M$ = 0…3.6 s) as well as for the transposition of the laboratory measurements to the natural scale.

The calculations, based on a mathematical model, made for the characteristics determination of the waves which can be produced in the laboratory channel and the experimental tests, have shown that the entire wave range present in the Romanian Black Sea seashore can be replicated on the used model.

Thus, for any type of float category wave energy capturing devices, model measurements for power and energy characteristics determination can be achieved for various combinations of wave height and wave period. By transposing this information to natural scale and using the wave appearance frequency distributions on height and period, the one year captured energy can be established in case of the Romanian seashore region by using the studied capturing device.

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