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Modelling of wave transmission through a pneumatic breakwater*

Maciej Paprota, Wojciech Sulisz
Institute of Hydro-Engineering of Polish Academy of Sciences, Gdańsk, Poland, E-mail: mapap@ibwpan.gda.pl

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Abstract: A theoretical approach is derived to study interaction of linear water waves with an air bubble curtain used as a pneumatic breakwater. Modelling of wave transmission through an aerial barrier is a complex task due to a need to cover processes associated with wave-current interaction, effects of two-phase flows, wave damping, etc.. An initial boundary-value problem is solved by applying an efficient eigenfunction expansion method and a time-stepping procedure. The derived semi-analytical solution is used to study the effect of basic parameters of the model on wave dissipative properties of the pneumatic breakwater. Results show that wave damping by the breakwater is mainly affected by an air flow rate. The increased air discharge results in higher velocities of ascending bubbles and increases aerial barrier width. This leads to a substantial reduction of transmitted wave heights, especially for waves of intermediate length and short waves. In order to verify the applicability of the presented theoretical approach, laboratory experiments are conducted in a wave flume for different wave regimes and pneumatic breakwater characteristics. The analysis of a wave transmission coefficient calculated numerically and measured in the laboratory confirms that the derived model can be used for a certain range of wave conditions.

Key words: Surface waves, wave transmission, wave-current interaction, pneumatic breakwater, numerical modelling

Introduction

Breakwaters are typical structures designed to protect harbours and coastal areas against wave attack. There are several types of breakwaters applied in a coastal zone. Most of them are heavy and expensive constructions. The cost of breakwaters increases with water depth and with severity of wave climate. An attractive alternative to traditional breakwaters are pneumatic curtains. The idea is based on generation of a vertical barrier consisted of air bubbles emanating from a perforated pipe founded on the sea bottom. The application of the air bubble barrier leads to wave energy dissipation and reduces the height of transmitted waves. Pneumatic barriers have several advantages in comparison with traditional breakwaters. In particular, it is easy to install such a barrier, the cost of construction is very low, this type of installation does not disturb ship traffic and remains neutral for natural landscape. Moreover, generation of additional circulation helps to maintain good quality of sea water. Despite the obvious benefits, pneumatic breakwaters remain an interesting scientific subject rather than a real problem of maritime engineering practice. This is mainly caused by a high power demand of air compressors providing sufficient amount of air required for an operation of pneumatic breakwaters. Low efficiency of aerial barriers in damping longer waves is another important drawback of the solution. On account of these facts, pneumatic curtains can be applied as temporal protection against short waves (e.g., protection of harbour entrance or waterways during storm events)[1] or can be combined with other coastal protection structures such as submerged and floating breakwaters[2].

The idea to construct an aerial barrier as a breakwater was proposed in 1907. This method was successfully applied to protect Standard Oil Company pier situated in El Segundo in California against wave action. First investigations suggested that wave damping by the pneumatic breakwater is a result of a current induced by air bubble motion[3]. Experiments performed in Californian Institute of Technology seems to support this hypothesis[4]. The idea of experiments was to generate currents set up by air injection or by water jets. The application of two types of current generation led to similar wave damping efficiency. Evans[3] conducted experiments to study the

* **Biography:** Maciej Paprota (1978-), Male, Ph. D.

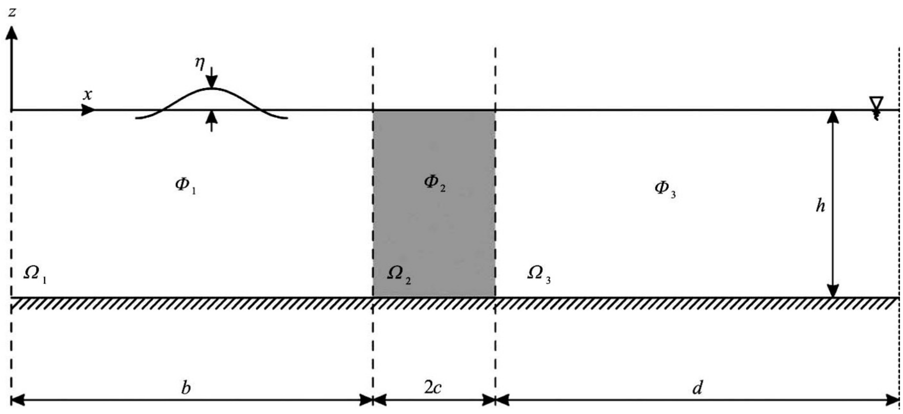

Fig.1 Definitions sketch and coordinate system

influence of a water jet on wave energy dissipation. The mean velocity of the opposing surface current necessary for complete damping was found to be proportional to the square root of wavelength. The results were similar to the results of the theoretical study performed by Taylor[5]. Consecutive experiments were conducted by Hensen[6,7]. Two wave flumes of different size were used. The smaller one was 0.5 m deep and the larger 1.15 m deep. Wave breaking was one of the reasons for higher damping rate. Experiments conducted in the field led to an interesting conclusion that the application of Froude similarity law to calculate the amount of air for different model scales was not an appropriate approach[7]. Preissler[8] derived a formula for the amount of air necessary to reduce the height of the incident wave by a certain value when passing through a pneumatic breakwater based on experiments conducted in a wave flume. A summary of analytical and experimental study on pneumatic breakwaters was provided by Bulson[9]. He proposed a formula for the amount of air necessary for complete suppression of incident waves. Brevik[10] applied the theoretical method proposed by Taylor[5], the perturbation approach of waves propagating in the presence of current proposed by Longuet-Higgins and Stewart[11], and wave breaking criteria to solve a problem of wave energy dissipation by the pneumatic breakwater. The presence of air bubbles was neglected in his considerations. Iwagaki et al.[2] investigated the effectiveness of pneumatic breakwaters in damping waves in combination with other types of breakwater. They concluded that the waves passing over the submerged breakwater transfer a part of their energy to higher frequency waves which can be efficiently damped by the pneumatic breakwater. Wang et al.[1] derived a similarity law for the amount of air necessary to generate wave damping barrier of specified parameters based on experiments conducted in a wave flume for three different model scales (1:10, 1:15, 1:30). Zhang et al.[12] studied numerically the efficiency of an air bubble curtain by applying a numerical model to a mixture of water and air. They applied a VOF method and solved standard k - ε equations with additional source terms in the governing equations. The theoretical results were compared with experimental data and the agreement was reasonable. Modelling of wave interaction with an aerial barrier is a complex task. The problem is that it is necessary to take into account processes associated with wave-current interaction, effects of two-phase flows, wave damping, etc. Therefore, the modelling requires an application of a complex numerical approach and is a challenging task[12].

In this paper a novel theoretical approach is adopted to study transmission of water waves passing a submerged air bubble curtain used as a pneumatic breakwater. First, an initial boundary-value problem is formulated and solved by applying the eigenfunction expansion method and a time-stepping procedure. Then, the derived semi-analytical solution is used to study the effect of the basic parameters of the model on wave dissipative properties of the aerial barrier and applied to study damping performance of the pneumatic breakwater in different wave conditions. Finally, the developed numerical model is verified based on data from laboratory experiments.

1. Theoretical formulation

1.1 *Statement of a problem*

The interaction of linear water waves with a pneumatic breakwater is considered (Fig.1). It is assumed that the fluid is inviscid and incompressible, the fluid motion is irrotational, and the sea bottom is horizontal and impervious. The area of action of the pneumatic breakwater with known damping properties is located in the middle section of the computational domain. A right-hand Cartesian coordinate system is selected such that x axis is horizontal and coincides with the undisturbed free surface and z points vertically up-