An Investigation of Wave Forces Acting on Vertical Coastal Structure

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Abstract. Research on wave forces attacking a vertical structure has been conducted worldwide. Morison’s equation commonly used to describe the phenomenon of the action for offshore structures, while for nearshore structures Goda’s equation is more reliable. Wave impact on vertical breakwaters is dangerous for vertical structures, both for walls and columns. Wave pressure distinguished for wave crest and wave trough, assumed to be distributed as a trapezoidal shape like along the vertical wall. The wave force consists of wave pressure on the front of the vertical wall and buoyancy, and uplift pressure in the vertical direction. In this research, a 2-dimensional physical modelling is carried out to observe the response of a vertical structure due to a wave action. Wave forces are measured using a flexi force sensor for both horizontal and vertical forces. Time series of incident wave and wave forces acting on the structure are recorded simultaneously and it clearly depicts the relation between them. The wave forces at the structure are linear to the height of the action waves. Periodical wave action results in the pushing forces at the structure to be higher than the pulling forces, as extra drift forces appear due to the shallow water wave condition.

Keywords: physical modelling, vertical coastal structures, wave forces

1. Introduction

Interaction between waves and structures creates a complex phenomenon. Variation of attack wave type gives a different phenomenon, and therefore should be depicted using specific approaches [1]. Three types of waves are considered, i.e., unbroken, breaking, and broken waves; while the structures are divided as vertical walls, sloping structures, and individual piles. In the case of waves attacking on a vertical coastal structure, the wave’s condition is breaking or broken waves and the structure is kind of a vertical wall. One of the most common formula used to calculate the situation is the Goda formula.

Based on the past approach, the empirical formulas have large enough discrepancy when met with real data. Hence, a set of physically-rational prediction formula was proposed [2]. It covers both quasi-statics and impact forces. The formula gave satisfactory results for certain range of parameter. But it is only suitable for vertical structures.

Experimental investigation of horizontal wave forces on vertical structures has also been conducted [3]. In this experiment, perforated caisson with single and double wave chambers as well as non-porous front walls was adopted as the vertical structure. The resulted data was then compared with Goda’s formula.
Numerical simulation was also carried out in order to investigate the phenomenon of wave forces on vertical structures in shallow water condition [4]. The simulation relied on full Navier-Stokes equation with Volume of Fluid surface tracking, resulted pressure and force that were comparable to the well proven empirical formula. It showed that the simulation tool has capability to verify the design of structures in coastal areas.

As there is not a really well-established formula to estimate the wave forces acting on a vertical structure in coastal area, a study has been conducted to depict the phenomenon. Scaled experimental simulation was chosen, as in this case, it is more suitable than other tools (for example numerical model simulation). It can immitate more real interaction on waves and vertical structures in shallow water condition than the numerical simulation.

2. Theoretical Background
Classical theory to estimate wave forces attacking a vertical structure are based on Goda’s formula. Wave pressure of vertical breakwaters are assumed to be distributed as a shape of trapezoidal along the vertical walls as depicted in the following figure [5]. The assumption applies for breaking and non-breaking waves.

![Figure 1. Distribution of wave pressure (after Goda).](image)

where:
- h : water depth in front of the breakwater
- d : depth above the armor layer of rubble foundation
- h' : distance from the water level to the bottom of upright section
- h_c : crest elevation of the breakwater above the water level

Factors are applied in the formula of wave pressure such as: wavedesign, maximum elevation of wave pressure, wave pressure on the front of vertical walls as well as buoyancy, and uplift pressure, described specifically in the original manuscript.

3. Experimental works
Physical modeling was carried out using a 45-m length 2-m width wave flume, equipped with a regular wave generator at one end and a wave absorber at the other end. As gravity and inertia forces are the dominant factor in this case, the hydraulic modeling follows the Froude Number criterion. Scale of 1:25 with undistorted model was adopted in this work.
3.1. Apparatus
The main equipment in the experimental work is a set of data acquisition tool that connects to the sensor of wave height and sensor for measuring incident forces, called flexiforce, as presented in figure 2 and figure 3 respectively.

![Figure 2. Set of wave height sensors installed in the wave flume for collecting wave data.](image1)

![Figure 3. The flexiforce gauge type SSK LB60-05K with force range of 4.9 N.](image2)

3.2. Simulation scenario
The vertical coastal structure consists of square sheetpiles mounted on the top by pile caps. In certain positions the group of sheetpiles is reinforced with raked piles. Scaled model of the structure is installed in the wave flume at the position of glass walls, so that the experimental could be observed well, as shown in figure 4. During the simulation, the wave forces acting on the piles is recorded through the flexiforce installed in a single pile located in the middle of the structure model (figure 5), while the wave data is collected using 10 wave height sensors as presented in figure 6.

![Figure 4. Model of the coastal structure is visible through the glass walls.](image3)

![Figure 5. Installation of flexiforce gauge in the single pile of the structure model.](image4)
4. Result and discussion
Wave behavior around the sheetpile structure is represented by the wave data on sensor 7 (in front of the breakwater) and sensor 9 (at rear of the breakwater). Data on the two sensors are normalized with data from sensor 1 which is the wave generation data, as presented in figure 7.

The graph in Figure 7 shows that the change in wave height in front of the breakwater rises linearly with an increase in incoming waves. The slope of the trend line is greater than 1, indicating that there has been an increase in wave height when it propagates to the structure. This is caused by the shoaling phenomenon, where sensor 7 is located in the area of the tilted bottom contour and is higher than the wave generator floor. In addition, the effect of wave reflection must be suspected. It is clear that vertical structures have the potential to reflect incoming waves.

The wave that occurs behind the structure, as recorded by sensor 9, are caused by transmission wave, which passes through the thin space between the sheet piles. In general, the magnitude of the transmission wave is about 1/3 of the incoming wave. Referring to the breaking waves criteria, where \(H_b = \frac{db}{1.25}\), commonly the waves at sensor 9 have already broken.

From the recorded wave data, there is a phenomenon of wave set down and wave set up. The wave set down is marked by the decreasing average value of the recorded water level elevation (wave) around
the wave breaking, on sensor 7 or 8. While the wave set up occurs at the upper end of the sloped contour and continues up to behind the structure as recorded on sensor 9.

The wave forces on the single sheet pile due to various incident waves have been analyzed and summarized as presented in figure 8.

![Figure 8. Relation of wave forces to the variation of wave height.](image)

The wave force presented in figure 8 above is the highest average value (positive) and the lowest average value (negative) of forces during the simulations. Based on the graph, the magnitude of the forward forces is always higher than the backward forces. This phenomenon is subject to the behavior of periodical wave action at shallow water wave condition, where extra drift forces appear.

The wave forces at the structure are linear to the height of the action waves. It happens when the incoming wave is still unbroken, as indicated by the graph at wave height less than 12 cm. After the wave height increase up to 15 cm, the wave condition is breaking and broken, the trend of the wave forces graph seem to be slowdown. This is an unexplained condition.

The more strange patterns appear for the wave height higher than 15 cm. The trendline of the positive and the negative forces is uncongruent, where the positive line jump up but the negative line also jump up. This phenomenon needs to be assessed. One of the suspect is the condition of wave overtopping.

5. Conclusions
The force caused by the wave impact is periodic and alternates according to the nature of the wave. Based on the test of the wave force model, it is found that the magnitude of the wave impulse is greater than the tensile force of the wave. This happens like the phenomenon of stokes drift in waves in shallow water. Commonly, the changes in the magnitude of the wave force occur linearly to changes in wave height.

6. References
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