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Experimental and Numerical Study on the Hydrodynamic Efficiency of Permeable Caissons Barriers

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Abstract

Breakwaters are constructed to protect beaches and ports from high storms and waves. By bringing calm to the port, breakwaters also increase ship safety and operation. This paper presents a study of the breakwater partially submerged in water, consisting of precast concrete caissons suspended on a spaced pile, experimentally and numerically, to assess the efficacy of hydrodynamics. A set of scenarios were simulated for the proposed breakwater using FLOW-3D numerical modeling. It turned out that the coefficient of wave transmission (K_t) increases with relative barrier draft and decreases with relative breakwater width. When the waves impacting breakwater are relatively short, their effectiveness rises. As the seafloor slope increases, k_t decreases. The suggested breakwater disperses the waves and reduces the wave speed behind it. The wave velocities and vortices surrounding the breakwater decrease as the wave period (T) increases. In front of the barrier and at the wave crest, hydrodynamic pressure is at its peak. The numerically simulated results using FLOW-3D program are consistent with the experimental results.

Keywords: Breakwater, Coastal, Caissons, FLOW-3D, Pile system, Waves, Numerical model

1. Introduction

The coastal region of countries is one of the important vital areas. The coastal area and the port have an important impact on national income, as they have an important role in promoting the development of urban areas and increasing and revitalizing coastal tourism [1-6]. Despite all this, natural phenomena negatively affect the beaches, such as tides, waves, and sea currents [7-10]. A breakwater provides a calm area for waves, greatly reducing wave energy so that ships can anchor safely and assisting in construction and mineral and oil exploration [11,12]. Traditional barriers such as rubble mounds and gravity barriers are used to reduce the negative effects of waves and to create a safe and calm marine area [13-15]. Furthermore, these breakwaters hinder littoral drift, which causes notable erosion or accretion [16,17]. In recreational ports, part of the waves are allowed to pass so that tourists are not exposed to danger or any inconvenience and provide a stunning view of the beach [18-21]. Many investigations have been carried out on barriers and the effect of their hydrodynamic properties on wave reduction, using a set of numerical and experimental models to evaluate hydrodynamic performance [22-30]. The hydrodynamic properties of the fixed floating barrier were investigated for waves [31,32]. Although a closed wall structure for barriers can successfully reduce wave disturbance to the harbor's waters, its restricted water exchange capacity can degrade the water quality of the harbor. Furthermore, sediment siltation may be exacerbated by decreased harbor flow velocities. Thus, in recent years, researchers have focused on permeable breakwaters. Horizontal perforated barriers, a sequence of vertical cylinders, slotted and porous barriers are examples of structures that enhancing port flow speed and environmental sustainability by facilitating water exchange and efficient wave dissipation [33,34]. A caisson barrier that used the staggered arrangement of wave chambers to decrease the wave energy and had perforations on both the front and back walls [35]. The transmission and reflection properties of regular waves through thin, perforated walls were studied [36]. The effectiveness of pile-supported barrier caisson has been studied [37-39]. This paper aims to assess the

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hydrodynamic efficacy of a partially submerged breakwater by conducting an experimental and numerical investigation of precast concrete caissons supported on spaced piles.

1.1. Advantages of Permeable Caisson Barriers

This type of breakwater is commonly used for the following purposes:

• It is used as a common solution in deep water conditions.

• It is used in soils with low bearing capacity.

• Effectively used in wave energy applications.

• Providing continuous refreshing water in the coastal region, which reduces pollution.

• It doesn't occupy a lot of space, therefore having no effect on seafloor living organisms.

1.2. Research Objectives

• Proposing efficient, economical breakwaters to protect beaches.

• Assessing experimentally and numerically the hydrodynamic performance of the proposed barrier.

2. Materials and Methods

2.1. Experimental Work

In this study, a wave flume length of 15.6 m in length, 45 cm in height, and 30 cm in width was used, which is split into three sections. These sections are the wave generator section and the wave absorber section, which are both connected to the testing part of the flume. The length of the working part is 12 m. Figure 1 shows the dimensions and details of the flume. The vertical sides are composed of 1.2 cm thick glass. Using various wave characteristics, the experiments were conducted to assess the hydrodynamic performance. The barrier was a caisson that was held up by a system of large, spaced piles. To provide the required wave periods, the wave generator's velocity was adjusted. To measure the wave height (H_t), a digital ultrasonic water surface measuring device was used. The details of barriers a caisson as shown in Figures 2 and 3. Table 1 contains a summary of the experimental parameters.

2.2. Hydrodynamic Parameter

Two parameters are used to evaluate hydrodynamic performance. The reflection coefficient (K_r), which measures how much energy the barrier reflects, is the first parameter and may be calculated as follows [40]:

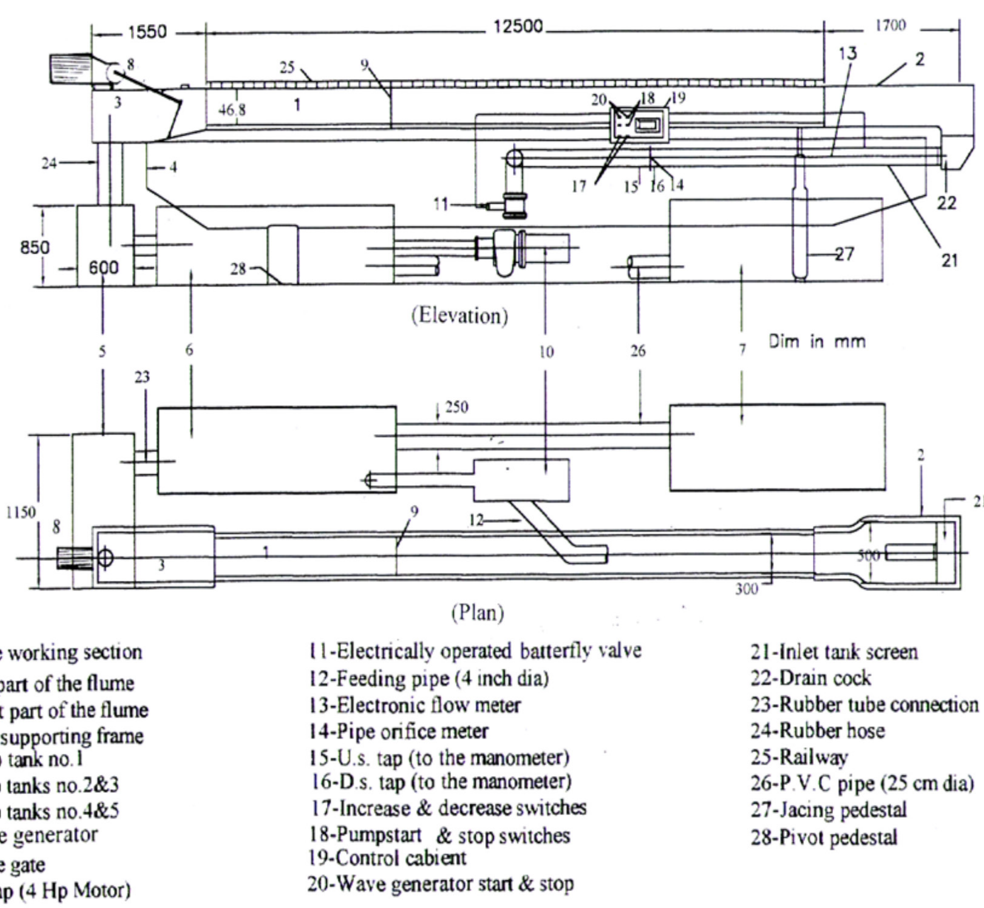

Figure 1. *Details of the wave flume*

$$K_r = \frac{H_r}{H_i} \quad (1)$$

Where: H_r is the height of the reflected wave, and H_i is height of the incident wave.

The second parameter is the height of the wave reflected by the incident wave, or the wave transmission coefficient (K_t), which can be calculated as follows [41]:

$$K_t = \frac{H_t}{H_i} \quad (2)$$

Where: H_t is the height of the transmitted wave.

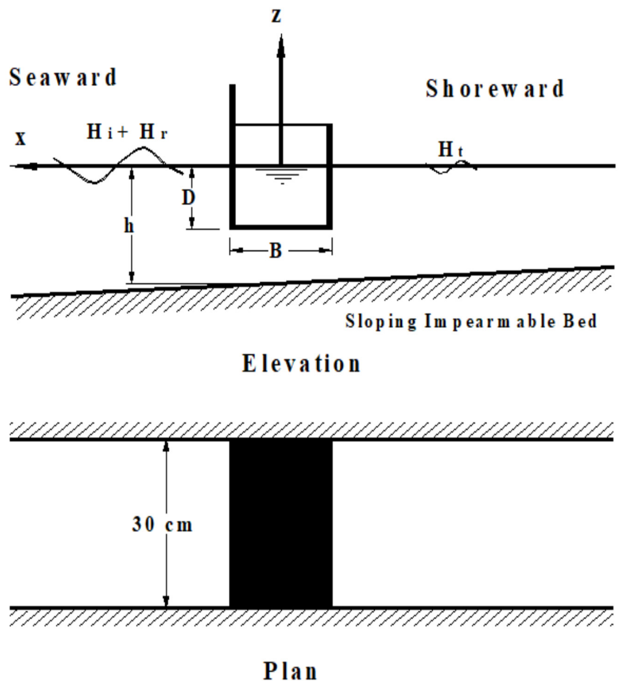

Figure 2. *Specifications of the pile system supporting the caisson on the solid bed*

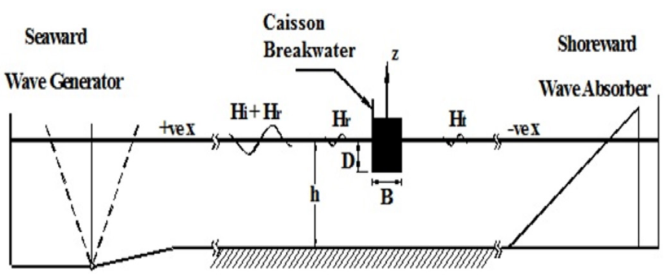

Figure 3. *Definition sketch for breakwater model*

Table 1. *Experimental parameters of the suggested model*

Parameter	Range of water levels
Depth of water (h)	20 (cm)
Width of barrier (B)	1, 20, 35, 50 and 65 (cm)
Wave length (L)	70-510 (cm)
Draft of barrier (D)	0, 6, 10, 14 and 18 (cm)
Bed slope (S_b)	0%, 2% and 4%

2.3. Numerical Simulations

The proposed barrier was numerically simulated FLOW-3D program. The hydrodynamic performance of the curtain vertical breakwater supported on piles was examined in this study using the computational fluid dynamics (CFD) methodology. The CFD uses computer-based simulation to analyze systems that involve fluid flow-related phenomena, including the motion of water waves. This method is quite effective and has many different engineering application areas. CFD can provide a faster and more economical solution than physical modeling [42]. Numerous applications are made possible by the suggested program's development base. The program's coding is based on finite volume theory, and the 3D Reynolds mean was calculated using Navier-Stokes (RANS) calculations [43]. In addition to traditional linear waves, FLOW-3D can simulate irregular and nonlinear waves [44]. The flow zones are separated into a grid of rectangular cells of varying sizes. Values for the fundamental flow quantities (such as velocity, pressure, and density) are kept for every cell [45-47]. The Fractional Area Volume Obstacle Representation (FAVOR) approach was used in the software to arrange the breakwaters system in the grids [48]. Figure 4 illustrates the numerical simulation process.

3. Results and Discussions

3.1. Experimental and Numerical Results

The experimental and numerical transmission coefficient results at B/h=1.5 were compared as shown in Figure 5. As Figure 5a illustrates, the experimental results at number of

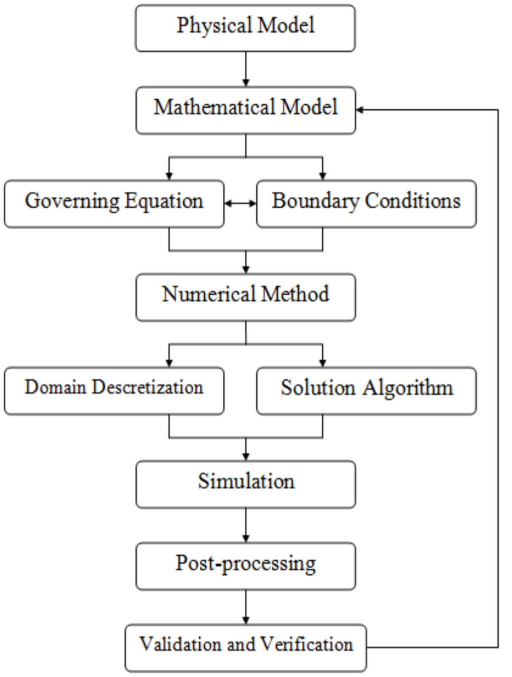

Figure 4. *Process for numerical simulation*

waves K_h=1.9 are consistent with the simulated values. It is also noted that as the draft increases, k_t decreases when D/h=0.4 is K_t=0.20, and when D/h=0.6 is K_t=0.10. The explanation for this is that the passage of water under the barrier decreases, and thus the dissipation of wave energy increases. Also, the width of the barrier increases the path of the waves below it, and thus the energy of the waves decreases. Furthermore, at number of waves (K_h)=1.06, the numerical model reduces k_t by roughly 7%, as shown in Figure 5b. In Figure 5b compared to Figure 5a, it is clear that k_t increases with the decrease in k_h, in Figure 5a at draft=0.2, water depth was 0.4 while in Figure 5b, at draft=0.2, the water depth was 0.7. Also, as in Figure 5a, it is noted that the values of k_t decrease with the increase in the values of the draft, but the agreement of the experimental results with the numerical results is not as accurate as the results when the wave number was equal to 1.9. Which indicates that increasing the wavenumber (i.e. increasing the number of waves per second) gives better compatibility results. Figure 5c illustrates the consistency among the experimental and numerical model results for K_h=0.75. The experimental and numerical K_t results at K_h=1. 9, 1.06, 0.75, and 0.4 when B/h=0.5 were compared in Figure 6. The results of experimental and numerical for various values of k_h showed that there was agreement between them, as seen in Figures 6a and 6b. Nevertheless, as Figures 6c and 6d demonstrate, numerical exceeds K_t from 7 to 13% for K_h less than 1.06 at D/h less than 0.6 at this point, so the numerical model is most accurate. The experimental and numerical K_t and K_r results at various D/h when B/h=0.5 is shown in Figure 7. For transmission coefficient, Figure 7 demonstrated that, for K_h values less than 0.8, the experimental results accord with the numerical results; however, for K_h values more than 0.8, the

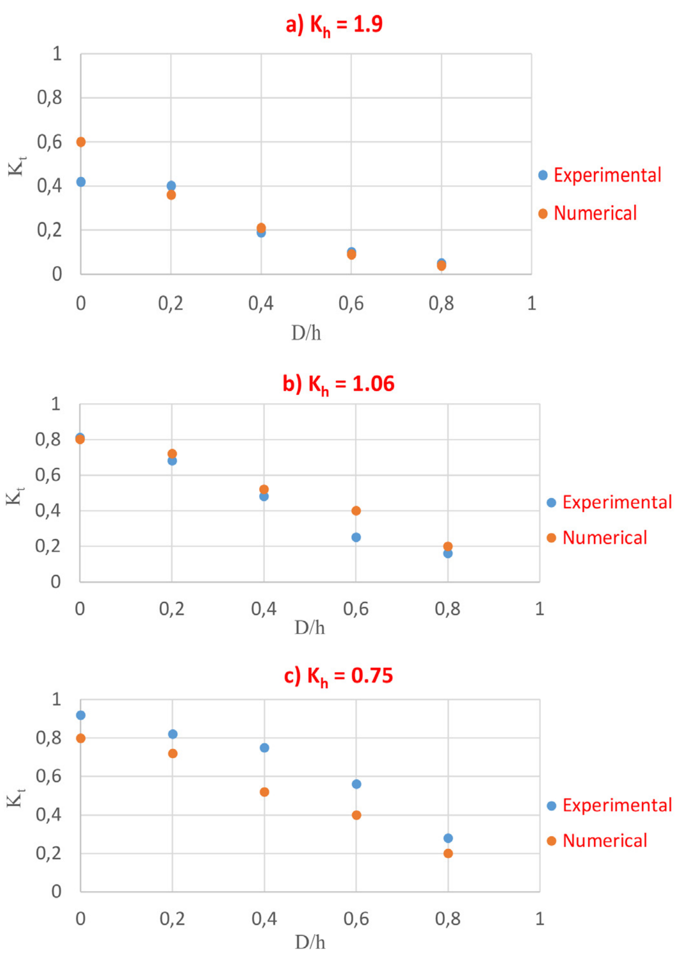

Figure 5. Comparison of experimental and numerical K_t results at B/h=1.5

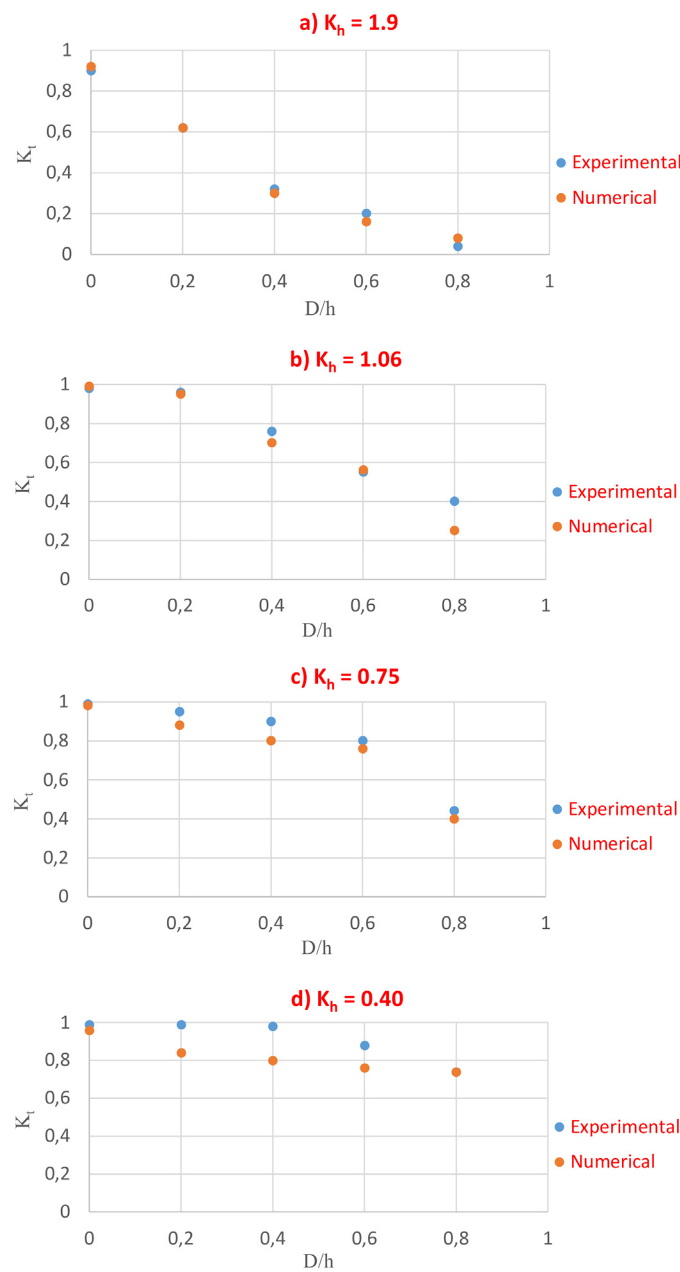

Figure 6. Comparison of experimental and numerical K_t and K_r results at B/h=0.5

transmission coefficient is exceeded by the numerical model by around 8 to 24%. Furthermore, Figure 7 demonstrates that for reflection coefficient, the numerical and experimental results agree when K_h is greater than 2.0, but when K_h is less than 2.0, the numerical model exceeds reflection coefficient by roughly 8-13%.

Figure 8 demonstrates a comparison between present study (experimental results) and various other similar studies for B/h=0.5 at D/h=0.30 and 0.60. The results showed that k_t values for this study are lower than those for previous studies under the same conditions. Figure 9 demonstrates the relationship between the numerical (K_t, K_r) and the wave number at different D/h at B/h=1.0 for experimental results. As K_h and D/h increase, K_t decreases, as seen in Figure 9a. However, Figure 9b shows that as K_h and D/h increase, the numerical K_r also rises.

3.2. The Impact of the Bed Slopes (S_b) on Hydrodynamic Performance

The relationship between B/h and K_t is shown in Figure 10 for S_b at K_h=1.88 and D/h=0.0, 0.2, 0.4, 0.6, and 0.8 for experimental results. The figure demonstrates that when B/h increases, K_t reduces for all bed slopes. Also, K_t decreases with increasing S_b. The breakwater was very efficient in reducing wave energy. This happens because of friction between the waves' transferred energy and the surface of breakwater, which causes more wave energy to be lost through the barrier. In addition to the vortices at the barrier's bottom end shedding during transmission. Moreover, Figure 8 demonstrates that kt reduces as D/h rises.

3.3. Hydrodynamic Pressure Distribution, Wave Velocities, and Vortex Formation Around Suggested Breakwater

Figure 11 illustrates the hydrodynamic pressure distribution caused by wave movement on the breakwater. The

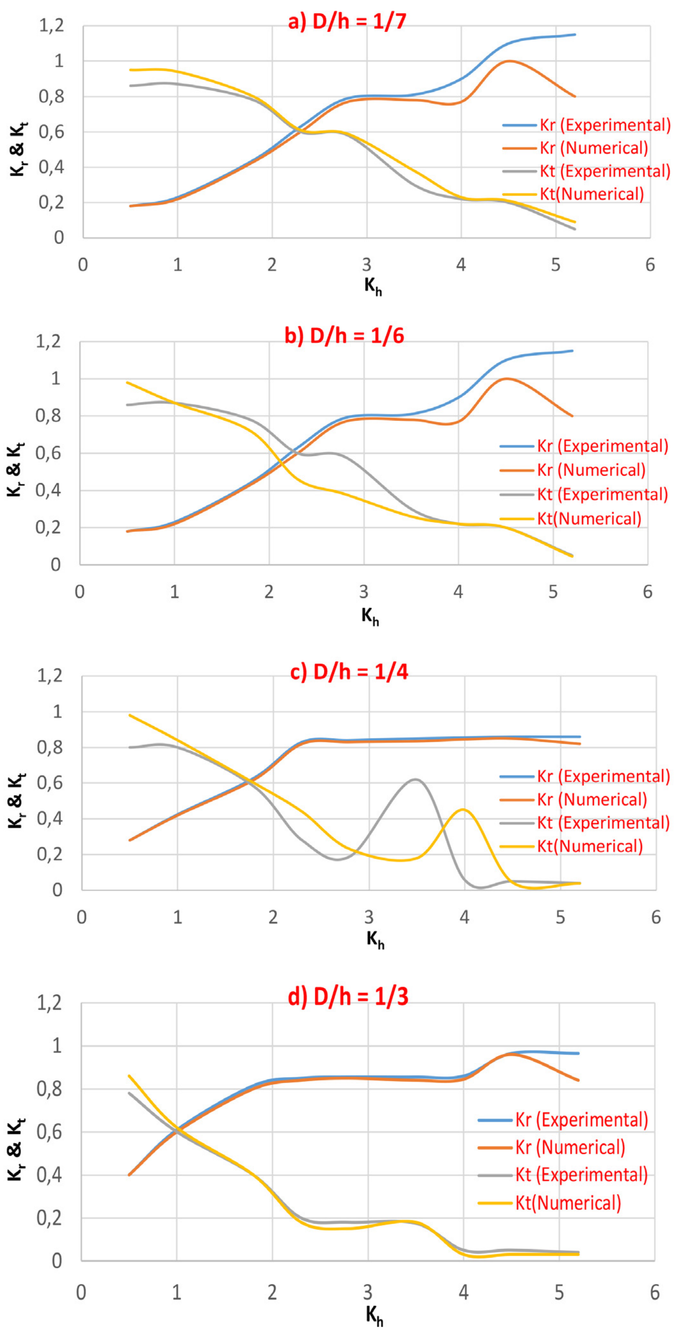

Figure 7. Comparison between Kr and Kt for different relative drafts at B/h=0.5

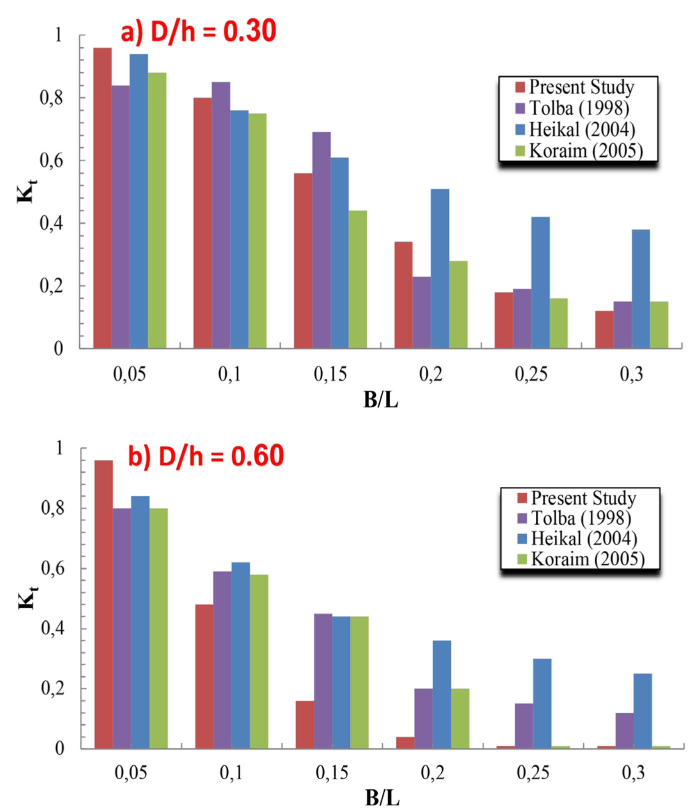

Figure 8. A comparison between K_t of this study and various previous studies

hydrodynamic pressure was strongest in front of the breakwater and close to the wave crest. The wave vortices surrounding the suggested breakwaters at various wave periods are seen in Figure 12. It was found that shorter wave periods also resulted in shorter wave lengths, which increased the number of vortices surrounding the breakwater. Hence, for T=1.1 s, the vortices in Figure 12b were larger than those in Figure 12a for T=1.3 s. It shows that the vortices surrounding the barrier expand as the wave period shortens. Figure 13 illustrates the wave velocities surrounding the barriers at various wave periods. It is evident from the figures that higher velocity was experienced around the barrier during shorter wave periods due to shorter wave lengths. The wave velocity rises surrounding the barrier as the wave period reduces, as shown in Figures 13a-c for T=0.8, 1.1, and 1.3 s, respectively.

4. Conclusion

These conclusions were drawn after analyzing the results as follows:

The transmission coefficient reduces with rising relative barrier width but rises when the barrier draft increases.

The transmission coefficient reduces as the seafloor slope rises.

The proposed breakwater scatters the waves through it and reduces the speed of the waves behind it.

The hydrodynamic efficiency of the barrier may be predicted using the suggested numerical model.

The hydrodynamic pressure and velocity field surrounding the barrier can be determined by the utilization of the numerical model.

The highest value of hydrodynamic pressure is at the wave crest and in front of the breakwater.

The simulated results using FLOW-3D program are consistent with the experimental results.

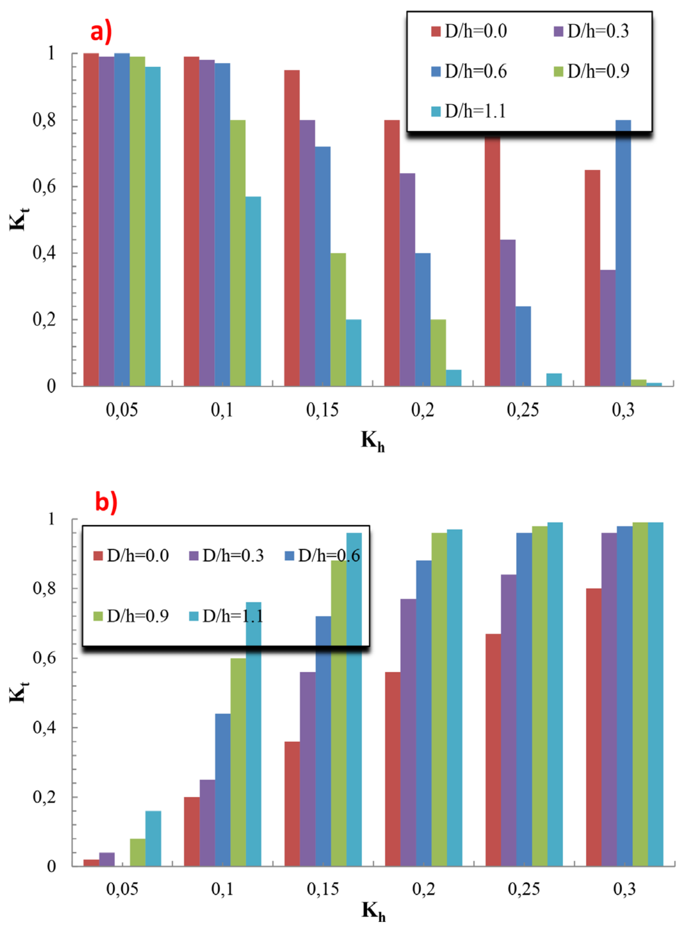

Figure 9. *K_t and K_r versus K_h at B/h=1.0*

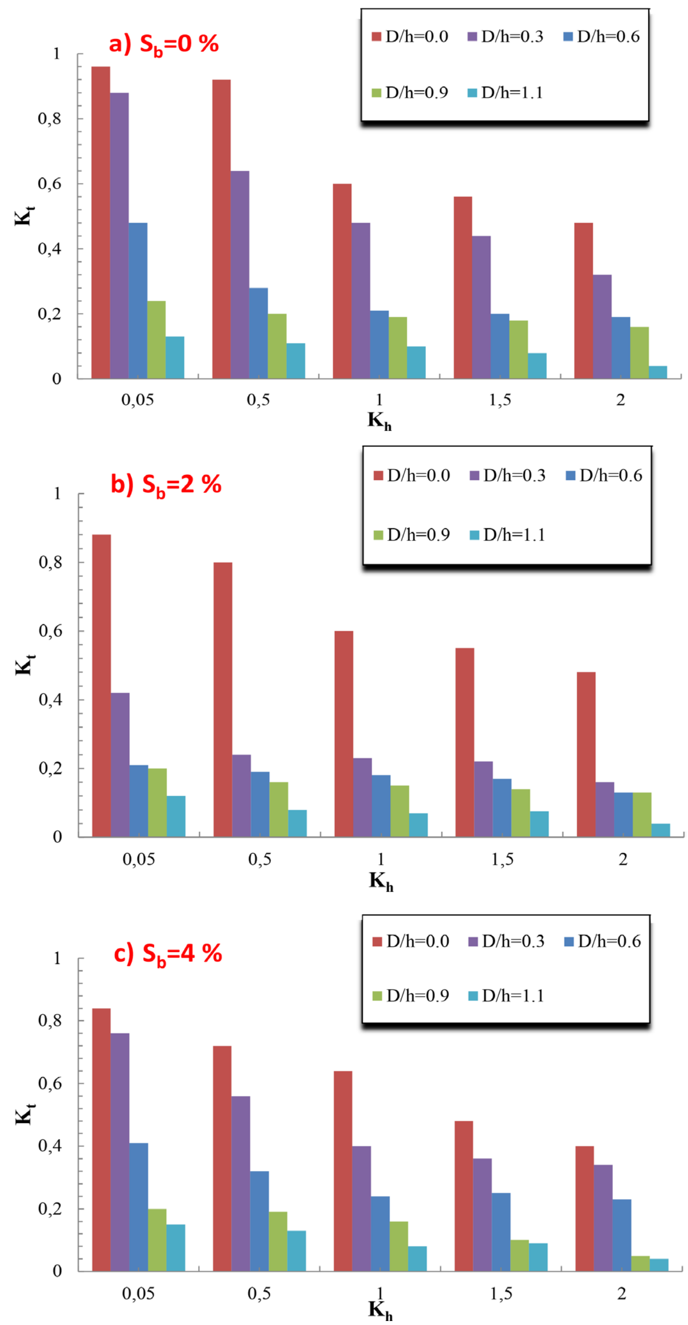

Figure 10. *K_t versus K_h for different D/h at S_b=0.0%, 2%, and 4%*

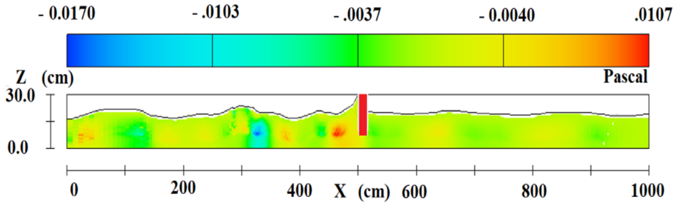

Figure 11*. Hydrodynamic pressure distribution surrounding the barrier*

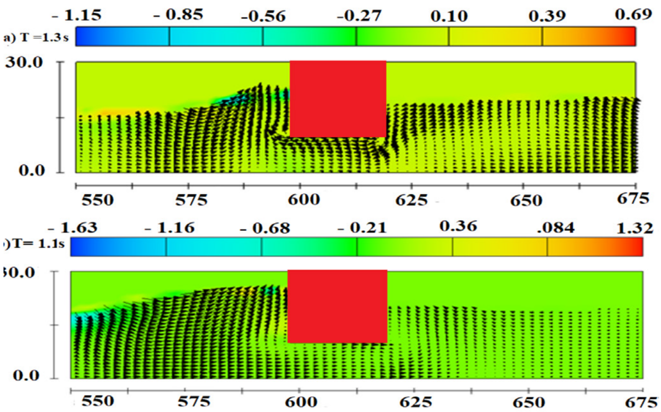

Figure 12*. Distribution of wave vortices*

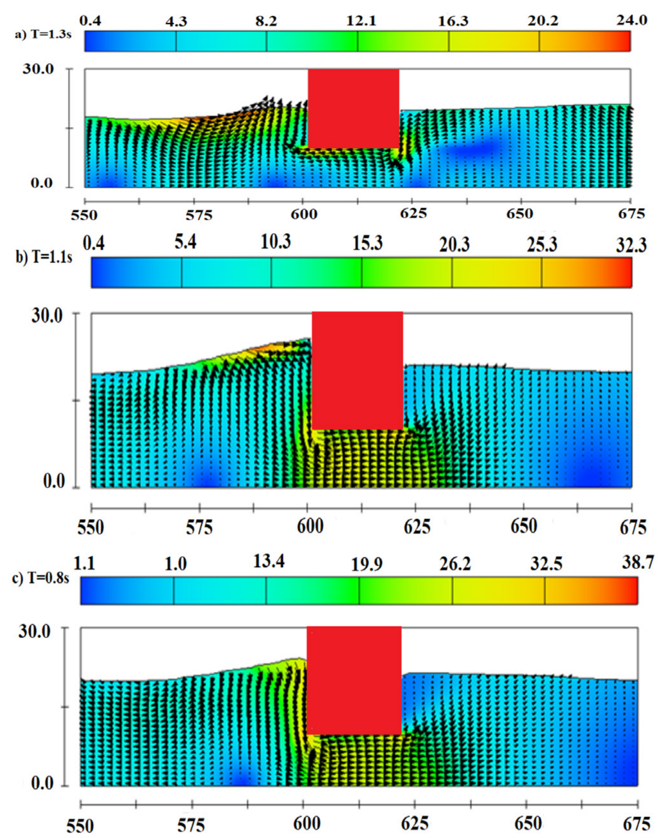

Figure 13*. Distribution of wave velocities*

Footnotes

Authorship Contributions

Concept design: K. B. Hussein, M. Ibrahim, and S. H. Abd El Ghany, Data Collection or Processing: K. B. Hussein, M. Ibrahim, and S. H. Abd El Ghany, Analysis or Interpretation: K. B. Hussein, M. Ibrahim, and S. H. Abd El Ghany, Literature Review: K. B. Hussein, and M. Ibrahim, Writing, Reviewing and Editing: K. B. Hussein, and S. H. Abd El Ghany.

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