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Experimental Study of Flow Fields around a Perforated Breakwater

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Abstract

This study investigates flow fields and energy dissipation due to regular wave interaction with a perforated vertical breakwater, through velocity data measurement in a two-dimensional wave tank. As the waves propagate through the perforated breakwater, the incoming wave energy is reflected back to the ocean, dissipated due to very turbulent flows near the perforations and inside the chamber, and transmitted through the perforations of the breakwater. This transmitted energy is further reduced due to the presence of the perforated back wall. Hence most of the energy is either reflected or dissipated in the vicinity of the structure, and only a small amount of the incoming wave energy is transmitted through the structure. In this study, particle image velocimetry (PIV) technique was employed to measure two-dimensional instantaneous velocity fields in the vicinity of the structure. Measured velocity data was treated statistically, and used to calculate mean flow fields, turbulence intensity and turbulent kinetic energy. For investigation of the flow pattern, time-averaged mean velocity fields were examined, and discussed using the cross-sections through slot and wall for comparison. Flow fields were obtained and compared for various cases with different regular wave conditions. In addition, turbulent kinetic energy was estimated as an approach to understand energy dissipation near the perforated breakwater. The turbulent kinetic energy was distributed against wave height and wave period to see the dependence on wave conditions.

Keywords: Perforated breakwater, Slotted wall, Experiment, Particle image velocimetry, Mean flow field, Turbulent kinetic energy

1. Introduction

Breakwaters have been constructed worldwide to prevent coastal erosion, provide a calm basin by reducing wave-induced disturbances for ships, and protect harbor facilities from rough seas. Rubble mound breakwaters are the oldest type, and have been widely used for sheltering harbors. However, innovative vertical structures like vertical caisson perforated breakwaters have became popular among coastal engineers, as they provide a better alternative to the classical types. Perforated breakwaters were first introduced by Jarlan (1961), and have advantages compared with other available types. His study concluded that significant damping of incoming waves can be achieved by the generation of eddies and turbulence near perforations in the front wall (Jarlan, 1961). Perforated breakwaters also reduce wave impact loads and wave overtopping (Isaacson et al., 1998). They also allow water circulation and rubbish clearance, creating a clean environment inside the harbor, and providing passage for fishes and microorganisms. They have become very popular in engineering practice due to their high effectiveness in energy dissipa-

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tion, and have been intensively investigated and are increasingly used.

Several analytical and numerical models of perforated breakwaters have been developed, but very few experimental studies have been done. The existing studies of perforated breakwaters can be categorized into a few groups. Most studies were conducted to investigate wave reflection due to varying wave parameters and geometry parameters of breakwater structures, using regular, normally incident waves (Kondo, 1979; Hagiwara, 1984; Bennet et al., 1992; Mallayachari & Sundar, 1994; Isaacson et al., 1998a; Zhu & Chwang, 2001; Requejo et al., 2002); there have, however, been a few studies for oblique incident waves (Suh & Park, 1995; Li et al., 2003). Urashima et al. (1986) developed a formula to calculate various design parameters, and Aoul & Lambert (2003) proposed a formula to find the pressure distribution and forces acting on the different faces of a perforated caisson breakwater. Some attempts have also been made to study breakwaters having more than two wave absorbers (Twu & Lin, 1991; Losada et al., 1993). In order to closer approach reality, Suh et al. (2001, 2006) studied wave transformation of irregular waves over perforated breakwaters.

Even though many analytical and numerical models have been developed to understand the phenomenon, laboratory experiments are necessary, due to the fact that flows near perforations are very chaotic, and numerical or analytical models have rarely modeled the complex environments in detail. Although the investigations have been analyzed for decades, most studies so far have focused mainly on free surface elevation changes. Hence there is a lack of quantitative measurements of velocity data in the vicinity of the structure, due to wave and structure interaction. Since perforated breakwaters dissipate energy, allowing flows into breakwater chambers through perforations, the lack of consideration of kinetic energy is likely to cause problems in studying interactive mechanisms between waves and slit structures, and in gaining a physical insight into the phenomenon.

The objective of the present study is therefore to investigate kinetic properties in the vicinity of a perforated breakwater structure, working from measured velocity data. This paper presents an experimental work on the velocity fields and turbulent kinetic energy distributions of a perforated breakwater due to wave structure interaction. The velocity fields in the vicinity of the structure were obtained using particle image velocimetry. Mean velocity and turbulence kinetic energy properties were extracted from instantaneous velocity measurements, through repeated experiments. The statistical approach was conducted according to phase averaging since waves are of unsteady nature. The velocity fields and turbulent kinetic energy distributions along both cross-sections of wall and slit were compared and discussed.

2. Experimental Setup

The experiments were performed in a glass-walled wave tank located at the Department of Civil Engineering of Texas A&M University. The wave tank is 36 m long, 0.9 m wide and 1.5 m high. The water depth was kept constant at d = 0.50 m throughout the experiments (Fig. 1). The wave-maker, of dry-back flap type, is installed at one end of the wave tank, and controlled by computer. A 1:5.5 sloping beach with a layer of horsehair at the other end of the tank absorbs wave energy and reduces reflection. A model structure of perforated breakwater was located 20.2 m away from the wave-maker, and rigidly fixed to the bottom. The model structure has slits on both the front and rear walls; the long vertical slits of 0.20 m high and 0.02 m wide are spaced 0.04 m apart. The front wall and slits of the model are sketched in Fig. 2(a).

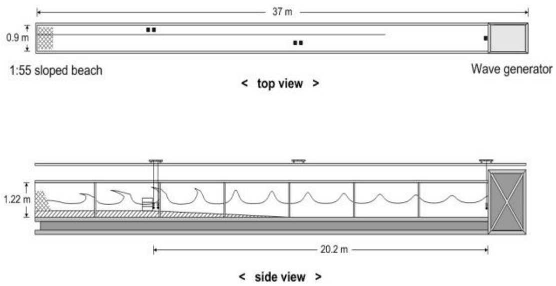
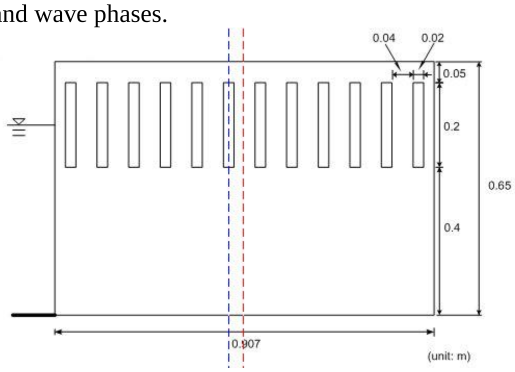


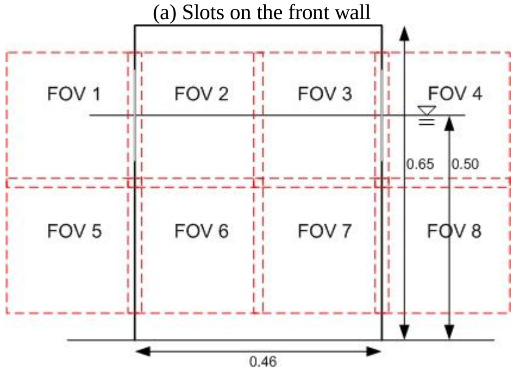
Fig. 1. Wave flume for the experiments

Particle image velocimetry (PIV) was employed to measure two-dimensional instantaneous velocity fields. PIV is a whole field measurement technique, which provides quantitative measurements of instantaneous velocity vectors with high accuracy, and without disturbing flows. In this study, in order to cover the required area in the vicinity of the model structure, eight fields of view (FOVs) each of size 25×25 cm^2 were used (Fig. 2(b)). To examine flow field variation with phase, the velocity fields were measured at ten different phases per wave. The phases for the wave measurements are depicted in Fig. 3. Since the perforated breakwater has vertical slits, two light sheets for PIV were used: one through the vertical slits; the other through the solid wall, as shown in Fig. 2(a). A program coded in LabVIEW was used to synchronize the wave-maker, the PIV system with a laser, and cameras for precise velocity measurements. The light source of the PIV system is a dual-head frequency-doubled Nd:YAG laser system that has a 532 nm wavelength, 400 mJ maximum output energy, 6 ns pulse duration, and 10 Hz repetition rate for each head. In the experiments, after preliminary tests and estimations of possible maximum velocities, the time duration between the pulses was kept at 3 ms. Two cameras with a resolution of 1004×1004 pixels, a dynamic range of 10 bit and a max. frame rate of 48 fps were used to capture the images and coupled for simultaneous measurements imaging 2 FOVs. The coupled cameras were likely to improve the measurements of continuous flow pattern in the vicinity of slots on the walls. For the mosaic measurements of the FOVs, the wave conditions were repeated for each FOV. In addition, for investigation of mean and turbulence properties, the instantaneous measurements were repeated. Image processing and post processing for velocity calculations were done using MPIV toolbox (Matlab toolbox for PIV, Mori & Chang, 2003). Initially, velocity vectors were calculated for a 64 x 64 pixels interrogation area, and then, based on the calculated values, more velocity vectors were again calculated for a smaller area of 32 x 32 pixels, with a 50% overlap. A median filter was subsequently applied to eliminate spurious vectors in the calculated velocity maps, and interpolation was used to fill in for the stray vectors. Smoothing was also done, using a weighted method based on eight neighboring points.

For the experiments, seven conditions of regular waves in an intermediate water depth were selected, with the intention of examining the effect of wave height and wave period on the wave-structure interaction of the perforated breakwater. The wave conditions of varying wave heights and wave periods are presented in Table 1. Each of the conditions was measured repeatedly for all of the FOVs and wave phases.



(a) Slots on the front wall



(b) FOVs

Fig. 2. Slots of the perforated breakwater and FOVs

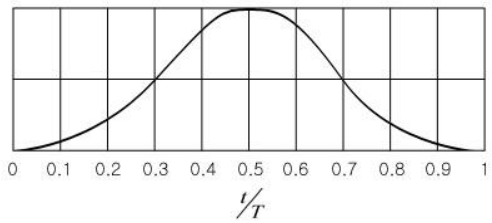


Fig. 3. Wave phases for the measurements

Table 1. Wave conditions for the measurements

	Wave period (sec)	Wave height (cn)
Case 1	1.0	4.0
Case 2	1.0	6.0
Case 3	1.0	8.0
Case 4	1.0	10.0
Case 5	1.6	8.0
Case 6	2.0	8.0
Case 7	2.5	8.0

3. Flow Fields

For the experiments, seven conditions of regular waves in an intermediate water depth were selected with the intention of examining the difference in velocity fields of the cross sections between slot and wall due to the wave-structure interaction of the perforated breakwater. The wave conditions of varying wave heights and wave periods are presented in Table 1. Each of the conditions was measured repeatedly for all of the FOVs and summed up for the whole field of velocity. From the repeated measurements, the mean velocity, mean turbulent intensity and mean turbulent kinetic energy were calculated for each wave condition. The instantaneous velocity measured by PIV can be decomposed into:

$$u_i = \langle u_i \rangle + u_i' \qquad (1)$$

where u_i is the instantaneous velocity, $<u_i>$ the mean velocity, u_i' the turbulent fluctuation, and subscript i the velocity component in the i direction.

The tendency of the flow fields was examined through time-averaged velocity fields. Fig. 4 shows the mean velocity fields under the waves in the vicinity of the perforated breakwater model. The velocity fields of the cross-sections through the wall and slot are presented in the figure.

For the light sheet through the slot, the flows transfer smoothly, even for small wave conditions like T = 1 sec, H = 4 cm, and clear continuity of the velocity fields is observed near the walls, which is indeed due to the slot. For most wave conditions, continuity of flows appears from before the front wall to behind the back wall. The flows near the free surface are violent, especially in the areas near the slots. Vortices form in front of the front wall, inside the chamber, and behind the back wall. The vortices in front of the front wall and behind the back wall are likely due to the oscillatory wave motion. The vortical flows inside the chamber are due to the inertia force from the incoming waves through the slot. Part of the incoming wave energy transmits through the front wall, and generates flows inside the chamber. The entrapment of flows inside the chamber causes the flow inside the chamber to be very violent. A large clockwise vortex appears inside the chamber. The velocity magnitudes are higher near the front wall than near the back wall. The energy of the flows dissipates when the flows penetrate through the slot, which results in the magnitude difference of velocities. As the wave conditions get larger (i.e. T = 1.6, 2, 2.5 s and H = 8 cm), the flows are disturbed, due to the presence of the slots in the walls, and small vortices appear near the free surface. Since flows move through the slots, these flows transfer energy to the flow fields inside the chamber and behind the back wall. While the flows along the slot show continuity, continuity is not observed along the wall. For the light sheet through the wall, when the waves come to the perforated breakwater structure, the flows do not show smoothly due to the presence of the wall. The difference in the flow pattern is seen clearly in the velocity maps. The discontinuity of velocity variations near both the front and back walls is indeed due to the presence of the wall. The flows along the wall occur due to energy transfer from the slot to the normal wall in the cross-sectional direction. In spite of the direction of the energy transfer, the main difference of flows between the slot and the wall is the flow pattern near the slot. As discussed above, while the flows through the slot show continuity, discontinuous flows are observed through the wall. Except for areas near the slot, the flows along both slot and wall appear very similar. In addition, the velocity magnitudes of the corresponding cases are close to each other. This is likely due to the short distance between neighboring slots, which leads to fast energy transfer to other regions. The slot distance effect on the flow pattern inside the chamber needs to be studied further. The wave conditions with longer wave periods show a larger velocity magnitude inside the chamber and behind the back wall. The waves with larger wave height and longer wave period tend to transmit more energy through the slots, which results in the pattern that the vortical flows inside the chamber appear very strong, compared to those outside the chamber. Since the energy is transferred, the kinetic energy of the flows inside the chamber is affected by the back wall as well as the front wall. In this study, although both walls had the slot condition, it is observed that the flow momentum in the leeside is relatively small. It might result from the change of the wave flow properties after passing through the front wall. The wave period, which is known to mainly influence the wave transmission, could be one of them.

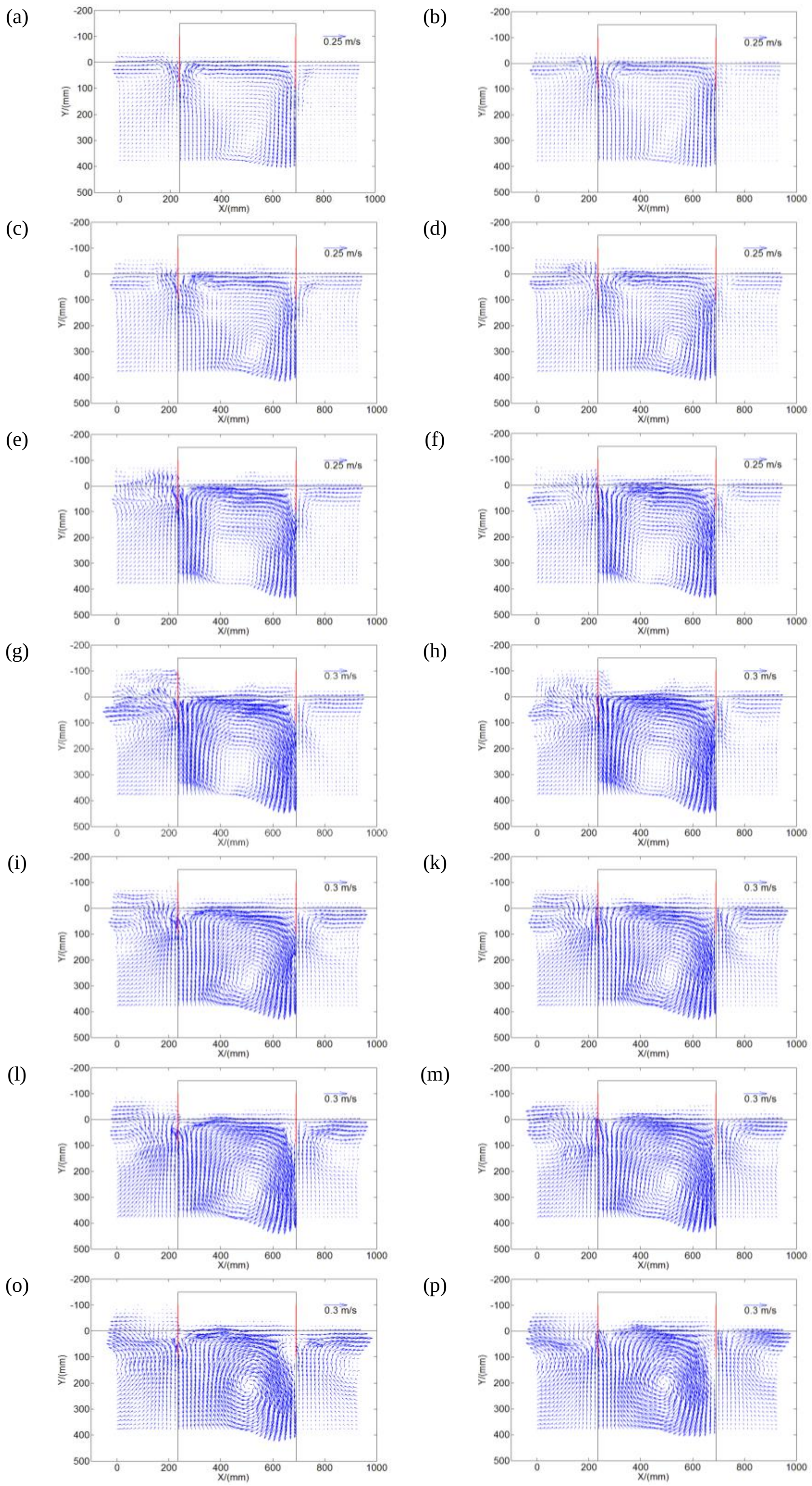


Fig. 4. Mean velocity fields over the perforated breakwater

4. Turbulent Kinetic Energy

The turbulent kinetic energy was estimated using the turbulent velocity obtained by statistical method. Since energy dissipation due to the slots of the breakwater is expected to occur through the turbulent nature of the flows, the turbulent kinetic energy is of importance in understanding the mechanism of the wave energy process over the breakwater. Using the velocity data, turbulent intensity and turbulent kinetic energy were calculated. The turbulent intensity for a 2D flow, I, is defined as:

$$I = (u'u' + v'v')^{1/2} \tag{2}$$

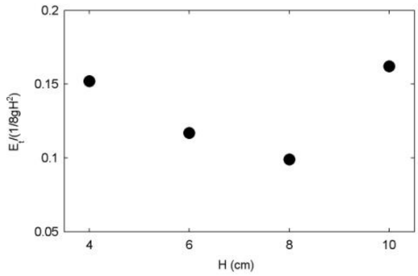
where u' and v' is the turbulent velocity in the x-direction and y-direction, respectively. The turbulent kinetic energy for a 2D flow, k_t, can also be defined as:

$$k_t \approx \frac{1.33}{2} I^2 \tag{3}$$

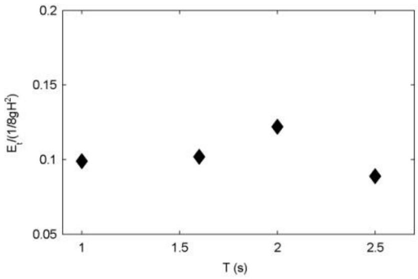
Eq. (2) is the formula suggested by Svendsen (1987) to estimate the turbulent kinetic energy of a 2D flow based on a 3D experimental approach. In this study, the estimation of properties is based on elements of the measurements (i.e. the resolution of the velocity map). Thus, the total kinetic energy, E_T, can be obtained as follows:

$$E_T = \frac{1}{T} \int_{t=0}^{t=T} \int_{z=0}^{z=\eta} k_t dz dt \tag{4}$$

where η is the wave elevation. Fig. 5 shows the total kinetic energy normalized by the total wave energy induced from the linear wave theory. In order to examine the dependence of each of the wave conditions, the total kinetic energy is plotted against the wave height and period, respectively. In the figure, the turbulent kinetic energy does not show significant dependence on wave height. Although wave height increases, turbulent kinetic energy decreases and bounces back. The increasing or decreasing rate is also insignificant. This could be because the energy distributed in the figure is normalized by the total wave energy, which is mainly dependent on the wave height. Thus, we expect that the turbulent kinetic energy increases with the increase of wave height; and we also need to interpret the distribution by consideration of the total wave energy. As for the distribution against the wave period, the turbulent kinetic energy increases as the wave period gets longer. As discussed, the total wave energy is linear-theoretically related not to the wave period, but to the wave height. That means the different cases in the figure all have the same total wave energy. If we exclude the influence of other factors, we can think of the larger transmission of longer waves as one of the causes of the finding. It is known that longer waves propagate to the breakwater; thus the more energy is transmitted, the larger the turbulent kinetic energy inside the chamber, which means that the perforated breakwater is more effective for wave absorption by longer waves.



(a)



(b)

Fig. 5. Turbulent kinetic energy in the chamber of the breakwater model: (a) wave height, (b) wave period

5. Conclusions

This study investigates the flow pattern over the perforated breakwater through the slot and wall. Since the perforated breakwater absorbs the wave energy by transmitting part of that energy through the slots, the kinetic energy inside the perforated breakwater is of importance for understanding how this works. For the investigation of the problem in this study, the wave fields under regular waves were measured, so that mean and turbulent flow fields were examined. Cross-sections through the slot and wall show the difference in flow pattern around the slot. The continuous flow pattern observed through the slot is not observed through the wall. However, except for the flow fields near the slot, the flow fields look very similar through both slot and wall. The flows with a vortex structure inside the breakwater chamber show stronger kinetic energy, when compared to those outside. The energy transferred from the incoming waves and captured inside the chamber likely leads to these flows. The vortices increase with increase of wave height and wave period. The flow pattern inside the chamber is of importance, since a perforated breakwater is primarily constructed to dissipate wave energy. In addition, a perforated breakwater can be a seawater exchange breakwater, by allowing flows from the weather side to the leeward side. The flow pattern inside the breakwater chamber is expected to give an idea of the effective energy dissipation and seawater exchange. The turbulent kinetic energy estimated from the turbulent fluctuations also shows a tendency to increase as the wave period increases. Against the change of the wave height, the turbulent kinetic energy normalized by the total wave energy from the linear wave theory does not show dependence.

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