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Wave Attenuation Properties of Composite Undulating Submerged Breakwaters

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ABSTRACT

This study investigates the attenuation of composite impermeable sinusoidal breakwater by physical experiment with combination of breakwaters collocated with various widths and heights. The breakwaters are located in different permutations and combinations from one set to three sets on the bottom as various undulating slope, and explore the attenuation effect when waves propagated through the periodic-gradational undulating terrain, the optimizations of a variety of sinusoidal breakwater are preliminary analyzed. This article discusses the properties of wave reflectance K_r, transmittance K_t, energy loss coefficient K_L, and the attenuation of such composite terrain, including optimal combinations of such obstacles. Desperate diversities are found in the K_r, K_t, and K_L, due to varied combination of the breakwater under the circumstances of various wave conditions. The results show that the attenuation of long waves is effective, and is affected by the nonlinearity and dispersion. The transmittance K_t shows that composite of rapidly varied combinations is better than a gradually varying section. Increasing the quantity of composite breakwater also improved the attenuation effect on both the rapidly varied cases and segmented gradually varying cases. The optimal combination to eliminate the energy of long waves is also discussed.

KEY WORDS: Composite undulating breakwater; reflection coefficient; transmission coefficient; wave attenuation; long wave.

INTRODUCTION

Offshore structures such as breakwater and seawall have been designed and constructed to get calmness by reducing huge wave force and that the urban safety is assured. In addition to safety factors, ecological, recreational landscape, reduce carbon emissions and other multiple factors are taken into account. Taiwan is surrounded by sea, due to the controls and restrictions on military purposes, coastal leisure activities are not widely implemented in the past. With the lifting of martial law, coasts are gradually opened for public use. In recent years, because of the saturation of land leisure, the land-based leisure industry has gradually moved toward the coast. There are many large and small ports, recreation and tourism and other activities flourish in the coastal space planning. In order to improve people's hydrophilic activity space, the new coastal wave-structure thus been extensively studied and discussed.

The recent emphasis on hydrophilic facilities has attracted interest because of increasing attention in the preservation of natural landscapes. The enforcement of a so-called amenity-oriented policy was subsequently established to promote the comprehensive development of port and harbor facilities, and many constructions are being developed using the ecological engineering method. Koftis et al. (2013) developed a large-scale experimental study of the effects of artificial Posidonia oceanica meadow on the wave height attenuation and on the wave orbital velocities. They interpreted that seagrasses have been referred to as “ecosystem engineers”, and the submerged vegetation attenuates mostly longer waves. Stratigaki el al (2011) and Sánchez-González et al. (2011) also performed similar experiments for the measurement of wave height attenuation, transmission and energy dissipation induced by a artificial submerged meadows of Posidonia oceanica.

On the other hand, many scholars have studied various offshore submerged breakwaters, including changing the external form and/or shape of submerged obstacles, the properties of permeability, the quantity of submerged obstacles, and the interval between each obstacle, and variation in wave conditions. Cho et al. (2004) investigated the occurrence of resonant reflection of monochromatic waves over an array of rectangular and trapezoidal submerged breakwaters by physical experiments. Their results exhibited the performance of trapezoidal shape is better than rectangular ones, and reflection coefficients of permeable breakwaters are less those of impermeable breakwaters.

Several related investigations are been carried out theoretically and experimentally for the predictions and discussion of the propagation of water waves over undulation seabed topography, and are mostly focus on the Bragg resonance problems which occurred between surface waves and undulated bottom. Davies and Heathershaw (1983) studied theoretically and experimentally the development of the wave field over the ripple patch, the resonance of surface waves due to bottom undulations has been successfully measured and discussed. Hsu and Wen (2001) developed a parabolic equation that includes higher-order bottom effect terms established to account for a rapidly varying topography and wave energy dissipation in the surf zone. Shu et al (1997) investigated the resonant Bragg reflection of monochromatic wave problems for wave propagation on rapidly varying topography based on high-order bottom effect terms proportional to the square of bottom slope and to the curvature. Cho and Lee (2000) investigate the propagation of monochromatic waves over an arbitrarily varying topography; a finite number of small steps represent the varying topography. Numerical model is developed to the study of the reflection cause by a singly- and doubly- sinusoidally varying topography. Feng and Hong (2000) suggested that the influence of current should be taken into account in simulating wave transformation in coastal area to avoid large discrepancies.

Porter and Porter (2001) considered the scattering and trapping of water waves by 3-D submerged topography. The interaction of linear surface gravity waves with 3-D periodic topography was concerned, considering that the scattering by the topography of parallel-crested obliquely incident waves and the propagation of trapping modes along the periodic topography are formulated and solved numerically. Moreover, Porter and Porter (2003) investigated the interactions between surface water waves and periodic bed forms in three different situations, including the scattering of given incident waves by finitely many periods of topography, and concern respectively the existence of unforced waves over periodically varying beds of infinite and finite extent. Thus, obtain the exact solution for ripple bed scattering based on full linear theory, with which they have compared previous approximations derived by using the modified mild-slope equation. The transfer matrix formulation can be applied to scattering by any topography, without incurring errors such as those that arise from bed discretization. In particular, the approach could be used to examine scattering by random periodic beds.

The performance of wave attenuation was also discussed by varying the quantity of submerged obstacles. Based on Miles' (1981) theory, Hsu et al. (2003) employed an evolution equation for mild-slope equation to study the Bragg reflection of water waves over multiply composite submerged breakwaters. Relative to the subject, they investigated numerically the Bragg scattering of water waves by multiply composite artificial bars based on the hyperbolic equation of Zhang et al.(1999). Their results exhibited the performance of the Bragg resonance for multiply composite artificial bars were greatly improved by increasing both the relative bar height and the quantity of bars with varied intervals. Shih et al. (2013) discussed the effectiveness of wave attenuation and the optimization of the disposition of sinusoidal breakwaters, physical experiments are carried out with various combinations of undulating breakwaters collocated with various wave conditions, including both the monochromatic and random wave tests. They exhibited that the tendency and fluctuating range of the values of the transmission coefficient K_r under long wave affections increases as dike heights increased, and contrarily trend to convergence and agglomerate when dike widths w (as defined in Fig.2) increased.

This article presents a discussion of the properties of the wave attenuation of the composite undulating submerged obstacles produced by various combinations of sinusoidal breakwaters. The diversity in the reflection coefficient, transmission coefficient, and loss coefficient caused by varied breakwater combinations under various wave conditions (i.e., wave heights, and wave periods) are discussed individually. This study also presents a discussion on the effectiveness of wave attenuation and the optimization of the disposition of sinusoidal breakwaters.

EXPERIMENTAL SETUP

Physical model tests were conducted in a 21-m wave flume located at the Fluid Mechanics Laboratory of Tungnan University (Fig. 1) to investigate the performance characteristics of composite undulating submerged breakwaters for long wave attenuation. The wave flume is 80 cm wide and 60 cm high, and the constant water depth is 25cm. The sinusoidal breakwaters are prefabricated in concrete individually of small pieces and are joined up to make a row (Fig. 2). The relative heights D/h of the undulating breakwater are 0.2, 0.4, 0.6, and 0.8, and the relative breakwater widths w/h are 0.4, 0.8, and 1.2. Performance of the composite undulating breakwater was tested by applying incident wave height of H = 2, 3, and 4 cm (H/h = 0.08, 0.12, and 0.16) with wave period T ranging from 0.5 s to 1.5 s (i.e., $\sigma^2 h/g$ = 4.024 to 0.447). A piston-type wave generator was located at one end of the flume with an absorbing 1:2.5 slope at the other end. The wave generator system was controlled by a wave generator filter unit produced by the Canadian Hydraulics Center (CHC). The performance of the designed concept was tested and validated using regular waves to assess the efficiency. Waves were measured using five capacitance wave gauges with an adapter linked to a personal computer. The model was installed in the middle of the tank 9 m from the generator.

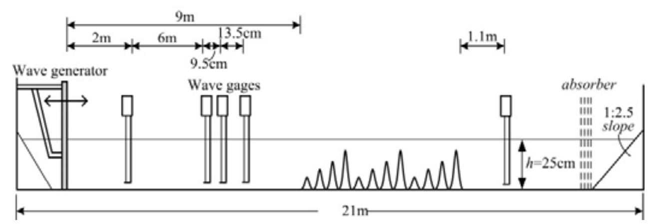


Fig.1 Schematic layout of wave flume and experimental setup

Fig.2 Illustration of sinusoidal obstacle

The breakwaters are located in different permutations and combinations from one set to three sets on the bottom as various undulating slope. Table 1 shows the composite of rapidly varied (Cases 1, 4 and 3) and gradually varying combinations (Cases 2 and 3) due to its envelope curve. The composite breakwaters were combined as a single-stage undulating terrain, also divided into multiple stages of undulation terrain to discuss the effect of the long wave attenuation. This study adopts an optimal combination of sinusoidal designed submerged breakwater to imitate this type of special terrain and explore these interactions, to investigate the relationship between the wave transmission, reflectivity and attenuation using a series of SIN-shaped obstacles with a combination of various width w/h and depth D/h of such sinusoidal breakwaters. A CCD camera (digital video camera) recorded the deformation of the waveform and wave-breaking effect to confirm the results measured by wave gauges.

ESTIMATIONOF WAVE ATTENUATION

The dissipation efficiencies can be estimated by the wave transmission coefficient. Postacchini et al. (2011) analysis the wave energy dissipation efficiency on seabed configurations with multiple vertical

Table 1. The combination of designed submerged breakwater

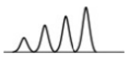
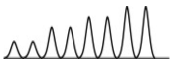
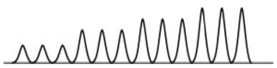
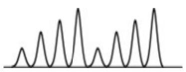
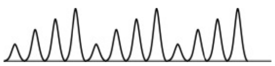
	Combinations of Sinusoidal breakwaters	Case	dike widths w (cm)
Case1		Case1-1	10
		Case1-2	20
		Case1-3	30
Case2		Case2-1	10
		Case2-2	20
		Case2-3	30
Case3		Case3-1	10
		Case3-2	20
		Case3-3	30
Case4		Case4-1	10
		Case4-2	20
		Case4-3	30
Case5		Case5-1	10
		Case5-2	20
		Case5-3	30

Fig.3 Illustration of composite sinusoidal submerged breakwaters

blades, inclined blades, and porous medium according to the dissipation efficiencies measured by the wave transmission coefficient. Pezzutto et al. (2012) investigate the influence on wave energy dissipation for a π-type floating breakwater by the dissipation coefficient distributions of related floating breakers examined with respect to two parameters: the wave period and wave steepness.

The wave attenuation of the present sinusoidal submerged obstacle can be estimate by the reflection and transmission of wave energy. The reflection coefficient are estimated by the method of Goda and Suzuki (1976) based on the time histories of water elevations, which are measured by five wave gages on the free water surface. To minimize the inaccuracy, the sampling time of data collections for reflection analyzing applied presently is adopted when the reflected waves from the obstacle reached the gauges, and stop before the re-reflected wave from the paddle approached. The amplitude are analyzed by the FFT (Fast Fourier Transform) technique, thus, the estimation of wave attenuation were estimated as follows:

According to Goda and Suzuki, the reflection coefficient, K_r, can be determined by:

$$K_r = \frac{a_r}{a_i} \tag{1}$$

where a_i and a_r are respectively the amplitudes of incident and reflected waves.

The wave transmission coefficients K_t were estimated by:

$$K_t = \frac{H_t}{H_i} \tag{2}$$

where H_i and H_t is the incident wave height and transmitted wave height, respectively. Consequently, wave attenuation (loss coefficient, K_L) can be determined from:

$$K_L = \sqrt{1 - K_r^2 - K_t^2} \tag{3}$$

RESULTS AND DISCUSSIONS

Wave decomposition and waveform variation

Figure 4 shows the variation of wave height attenuation when waves propagated through the submerged obstacles, showing that the wave height decreased significantly when wave period is T =0.5 s and related wave height H/h = 0.16. In the same arrangement, when the wavelength increases (wave period T = 1.5 s) and wave height H/h = 0.16, the attenuation efficiency of transmitted wave is better than short-period waves, due to effect of the interaction of submerged breakwater, tiny disturbance appeared on the crest, which is known as dispersive waves, i.e. wave splitting. Long-period waves affected the impact of nonlinear and dispersion properties, the occurrence of wave decomposition appears after the breakwater, as well as phenomenon of high frequency

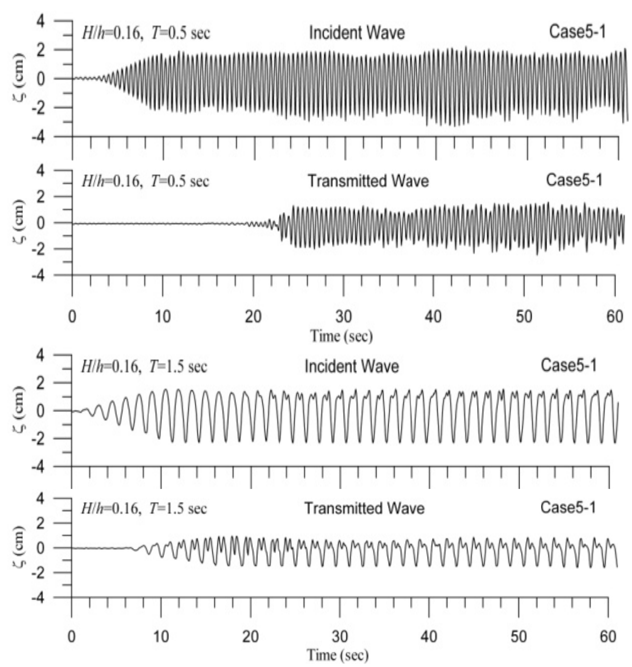


Fig. 4 Variation of waveform of incident and transmitted waves (T = 0.5 s and 1.5 s)

components in the volatility process. The phenomenon of wave decomposition produces relatively high frequency harmonic waves, which possibly determine the dissipation on long wave energy. Figs.5-6 show the attenuation process of incident wave by combinations of three sets of rapidly varied sinusoidal breakwater at T = 1.0 s and 1.5 s when w/h = 0.4.

Fig. 5 Attenuation process of incident wave by combinations of three sets of rapidly varied sinusoidal breakwater at T = 1.0 s when w/h = 0.4

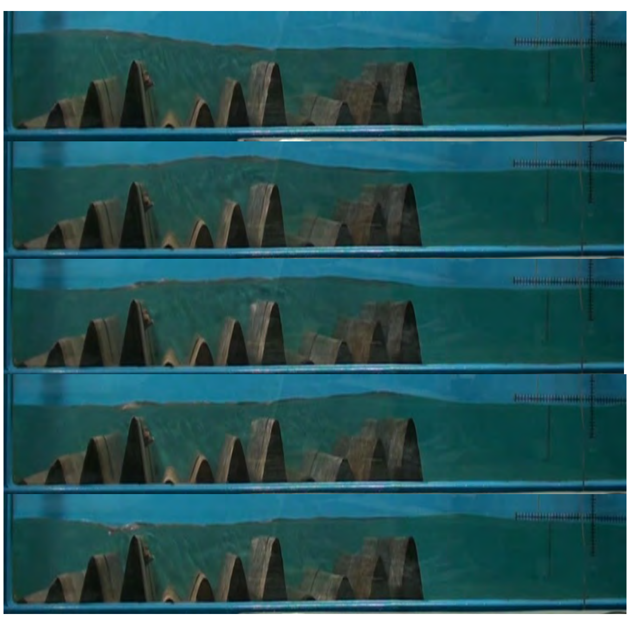


Fig. 6 Attenuation process of incident wave by combinations of three sets of rapidly varied sinusoidal breakwater at T = 1.5 s when w/h = 0.4

Arrangement and energy dissipation

Transmittance relative to breakwater configuration

Fig. 7 shows the variation of transmission coefficient K_t when waves propagated through the submerged breakwater under the configuration of five different combinations in Table 1. When the width of the submerged breakwater is w/h = 0.4, a gradient sloping undulating terrain is formed by combining (simultaneously) respectively a single row, double rows and three rows of sinusoidal breakwaters with various height D/h varied from 0.2, 0.4, 0.6 to 0.8 in order, denoted as Case 1 to Case 3. The results show that, by comparing the results from Case 1 to Case 3, the variation of wave transmission in Case 2 increased initially and then decreases when the wave period increased, however, there is no significant discrepancy in the overall tendency of the variety of transmittance for the other two cases. Except for Case 2-2, the transmittance of long-period waves has declined and decreased from 0.9 (T = 0.5 s) to 0.7 (T = 1.5 s) when the breakwater width increased to w/h = 0.8 and w/h = 1.2. The overall tendency of the variety of transmittance reveals that the transmittance increased as the breakwater width increases, and the attenuation in transmitted waves is ineffectiveness. This illustrates that the increasing of breakwater width increases the length of the undulation terrain but gentled the average slope.

The breakwater is optimized as segmented and rapidly changed terrain, arranged as Case 1, Case 4 and Case 5. When the width is w/h = 0.4, the breakwater is arranged cyclically with D/h = 0.2, 0.4, 0.6 and 0.8, respectively, forming a multistage (one to three stages) and rapidly varied steep wavy sloping terrain.

Fig. 8 found that when w/h = 0.4, the transmittance K_t in Case 1 to Case 5 reveals that: a piecewise- rapidly varied terrain is more effective than a unitary-gradually varying topography, the transmittance is significantly improved, and the minimum K_t value occurs in Case 5. K_t decreases from 0.7 to approximately 0.4 with the increasing in wave period and/or wavelength. Similarly, when the embankment width increased to w/h = 0.8 and w/h = 1.2, we found that the results of rapidly varied combinations series (Case1, Case4 and Case5) is similar to that of unitary-gradually varying cases (Case1 - Case3). Increase the breakwater width reduces the average slope of each segmented composite breakwater, i.e. decreases the angle of the envelope curve of the terrain, and resulting in increasing rather than reducing wave transmittance. This phenomenon is approvable with the investigating results on the efficiency of wave energy dissipation by varying the angle of breakwaters, e.g. Lorenzoni et al. (2010) reveals that the total horizontal force on 45° inclined blades is about 50% larger than that on vertical blades and the drag forces are stronger than the inertia ones. The results also agreed with the study of Nobuoka et al. (1996), which showed that the structure with multiple blades inclined by 45° caused the most strong onshore currents on the side of structure.

Fig. 9 shows the variation of transmission K_t, reflectance K_r, and loss coefficient K_L when the breakwater width varied from w/h = 0.4, 0.8 to 1.2, was also found in Case 5 the minimum transmittance and reflection, when w/h = 0.4. Regardless of breakwater width, both the reflectance and transmittance decreased as dimensionless frequency $\sigma^2 h/g$ decreased (increasing in wavelength). However, in terms of energy loss coefficient K_L, the variation of K_L mainly distributed between 0.6 and 0.95, and is incremented with the reduction of the dimensionless frequency, indicating that under the combination of Case 5, and when w/h = 0.4, this combination is most effective for long-wave attenuation.

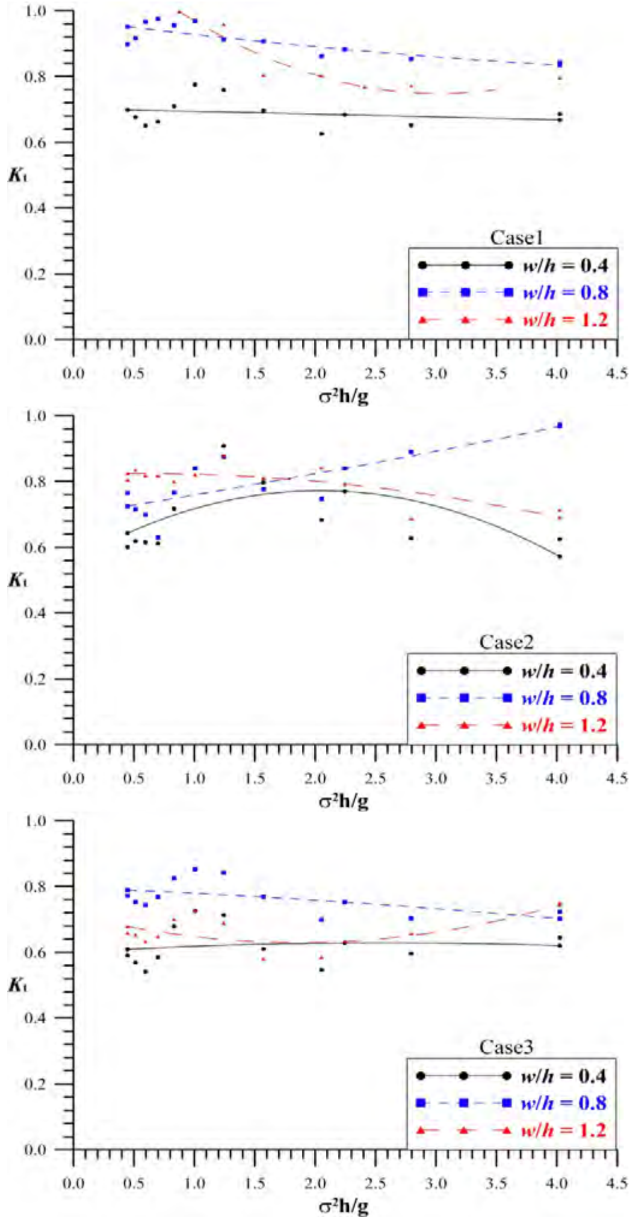


Fig. 7 Variation of transmission coefficient K_t versus $\sigma^2 h/g$ under the configurations of the cases 1, 2, and3

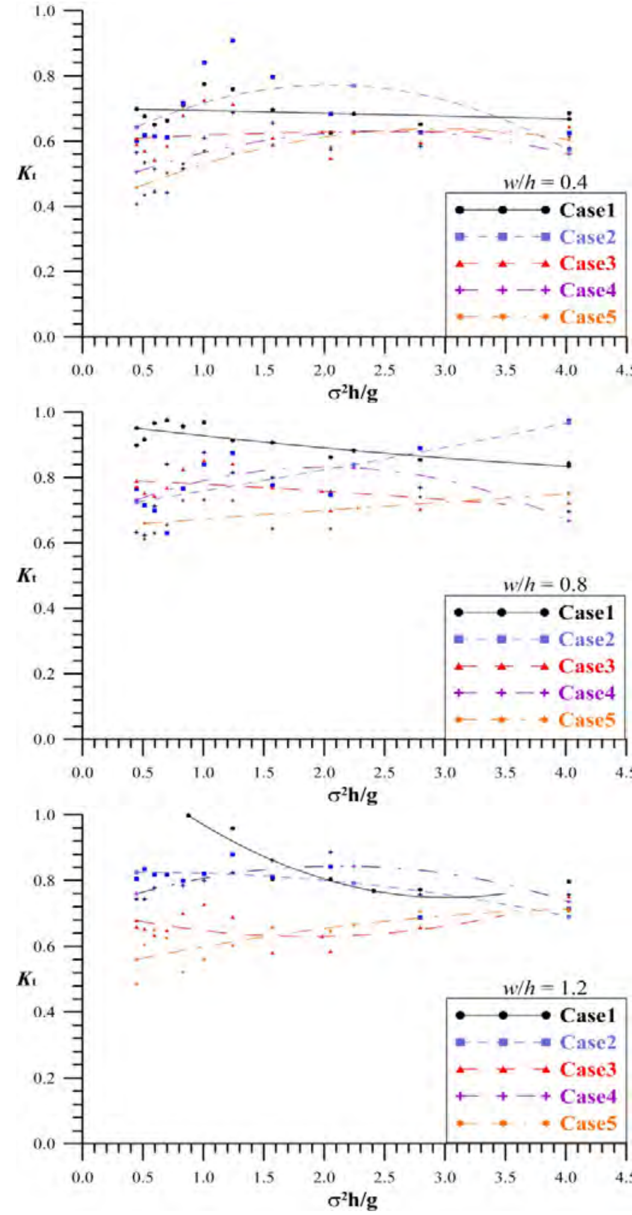


Fig.8 Variation of transmission coefficient K_t versus $\sigma^2 h/g$ under the configurations of case 1 to 5 with w/h = 0.4, 0.8, and 1.2

Variation of K_t, K_r, and K_L related to breakwater composition

Experiments were carried out to investigate the variation of breakwater width on the impact of reflection coefficient, transmission coefficient, and energy loss coefficient by the combination of 1-3 groups of sinusoidal breakwaters varied gradually from D/h = 0.2 to 0.8 in order, as shown in Table 1 the unitary- undulating sloping terrain expressed as Case 1 to Case 3. As shown in Fig. 10 the results when w/h = 0.4, revealing that the impact of composite group number (seabed slope length) is inconspicuous with less correspondence between wave reflection coefficient K_r and the wavelength, the K_r values are distributed among 0.5 to 0.9 when dimensional frequency is $\sigma^2 h/g$ = 0.5-4.0. The reflectivity decreased initially, but then increased when wave frequency increased, the reflectivity is minimum among $\sigma^2 h/g$ = 1.0 to 3.0, and is relatively greater for short period wave. However, the reflectance curve on Case 1 for long-period waves ($\sigma^2 h/g$ < 1.0) improved significantly from 0.12 to 0.45. Moreover, the reflectance of unitary- undulating sloping terrain with one set of varying sinusoidal breakwaters (Case 1) is more efficiency than that of duplicate arrangement with 2 and 3 sets (Case 2 and Case 3), same consequences are also found when w/h = 0.8, and w/h = 1.2. Besides, the results of rapidly varied combinations series (Case 1, Case 4, and Case 5) when w/h = 0.4 are shown in Fig. 11. The variations of transmittance K_t arranged with one and two groups were inconspicuous, which are ranged between 0.5 and 0.8, and similar with that of unitary- undulating

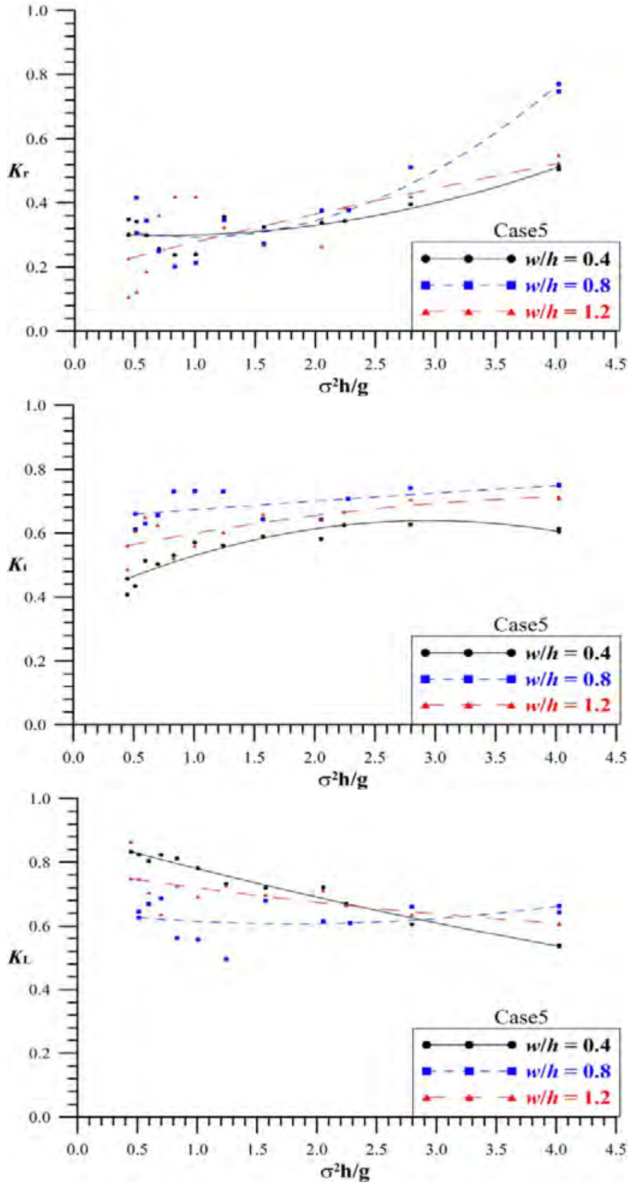


Fig.9 Variation of K_r, K_t, and K_L versus σ^2h/g under the configurations of case 5 with w/h = 0.4, 0.8, and 1.2

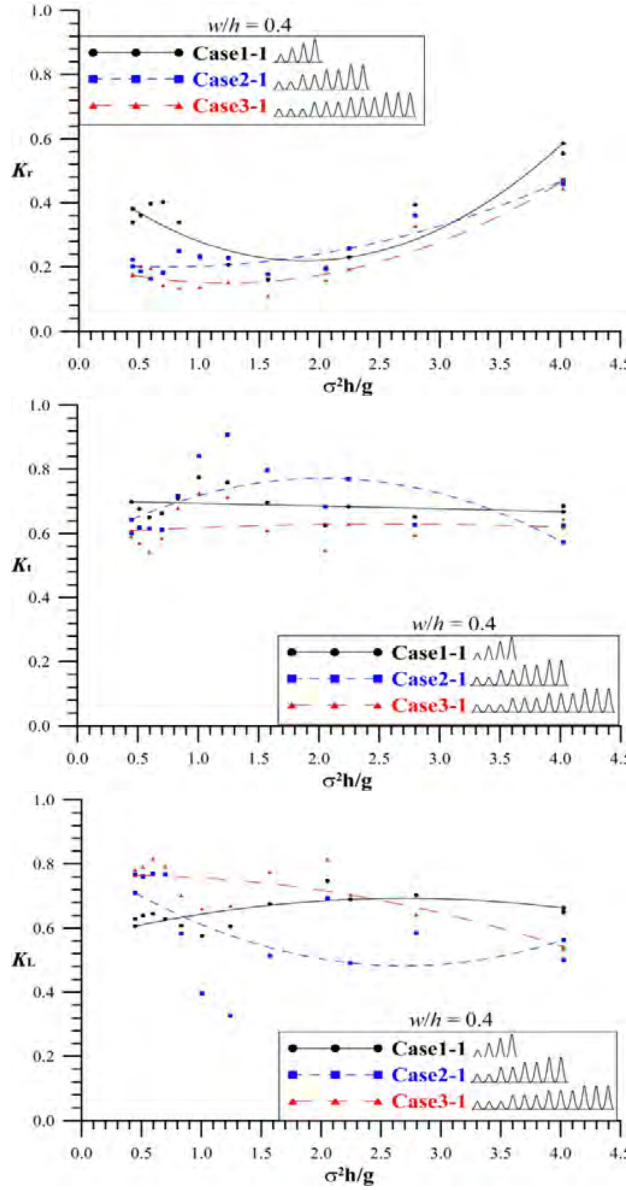


Fig.10 Variation of K_r, K_t, and K_L versus σ^2h/g when w/h = 0.4 under the configurations of case 1, 2, and 3

sloping terrain. But in three groups case (Case5), transmittance K_t decreases with the increasing of wavelength, which reduced to 0.4 from 0.7 (compared that with Case 1), and revealed that the composite breakwater in Case 5 is most effective for the attenuation of long wave energy among the five different configurations.

The variation of reflectivity K_r curve decrease initially and then increased in Case1-1 when w/h = 0.4, however, the overall variation tendency of reflectivity displayed that they increase as the wavelength decreases, and is relatively minor in σ^2h/g = 1.0 to 3.0. The reflectance affected by long-period wave is most efficiency in Case 1, whereas in Case5, the reflectance decreases to 0.4 (long period waves) from 0.7 (short period waves) when the wavelength increased. As shown in Fig. 11 when w/h =0.4, the variation of energy attenuation in Case 1 reveals that K_L decreased as σ^2h/g decreased, but increased as σ^2h/g decrease correspondingly when the arrangement of segmented breakwaters increased to 2 and 3 sets (Case4 and Case5). The attenuation for the repadly- gradually varying cases acquire a most effective combination when 3 sets of breakwaters is arranged, which the energy loss coefficients are approximately between 0.7 and 0.9.

The results showed that under these five configurations, the arrangement of three sets of rapidly varied sinusoidal breakwaters (Case 5) have the most significant effect for the attenuation of long waves. Compared with the results in Fig. 9 further informed that for w/h = 0.4, 0.8, and 1.2, the attenuation is most effective when w/h = 0.4 (i.e. Case 5-1), which is identified as the best configuration (optimal combination) for the composite undulating breakwaters.

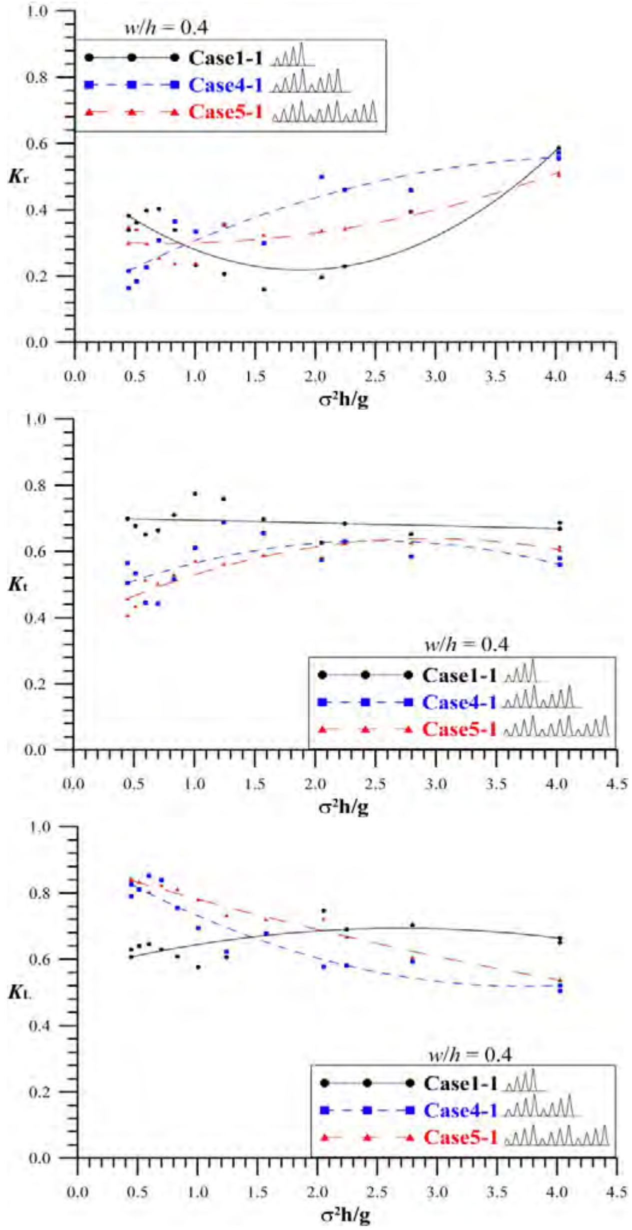


Fig.11 Variation of K_r, K_t, and K_L versus σ^2h/g when w/h = 0.4 under the configurations of Case 1, 4, and 5

CONCLUSIONS

The experimental results showed that the composite undulating breakwaters have significant efficiency on the attenuation of long period waves. A gradient sloping undulating terrain is formed by combining the sinusoidal breakwaters with various heights D/h varied from 0.2 to 0.8 as various undulating slopes, and investigate on the attenuation efficiency of periodical waves propagated over such undulating terrain with gradually increased shoaling effect, forcing the long period waves to collapse over the breakwaters gradually. Preliminary test results obtained the following conclusions.

Wave decomposition appeared as long-period waves propagated over the submerged obstacles due to combined effect of nonlinearity and dispersion properties, with the existence of high-frequency component wave phenomenon, which usually play an important role in the attenuation of long wave energy.

The variations of K_t from Case 1 to Case 5 expressed that, a piecewise-rapidly varied terrain is more effective than a unitary- gradually varying topography, which the transmission coefficient was significantly reduced. The transmittance on the whole is minimal with a significant reduction as the wavelength increased in Case 5 (with 3 sets).

In both the piecewise- rapidly varied cases and unitary- gradually varying cases, attenuation efficiency increased with duplicate arrangement of multi sets of undulating breakwaters, especially for long-wave attenuation. Furthermore, increasing the breakwater width reduces the average slope of each segmented composite terrain, deteriorating the efficacy of wave attenuation.

Among the five configurations, the arrangement of three sets of rapidly varied undulating terrain in Case 5 is most efficiency for long wave attenuation under the condition of w/h = 0.4 (i.e. Case 5-1) identified as optimal composite undulating breakwaters.

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