

Experimental Study on Wave Transmission and Reflection at Impermeable Submerged Breakwaters

Amin Mahmoudi^{1*}, Habib Hakimzade², Mohammad Javad Ketabdari³, Nick Cartwright⁴,
Mohammad Vaghefi⁵

¹ Assistant Professor of Hydraulic Structures, Civil Engineering Department, Persian Gulf University, Mahini Street, Bushehr, a_mahmoudi@pgu.ac.ir

² Professor, Faculty of Civil Engineering, Sahand University of Technology, Tabriz; Hakimzadeh@sut.ac.ir

³ Associate Professor, Faculty of Marine Technology, Amirkabir University of Technology, Tehran, Ketabdar@aut.ac.ir

⁴ Griffith School of Engineering, Griffith University, Queensland, 4222, Australia, n.cartwright@griffith.edu.au

⁵ Associate Professor of Hydraulic Structures, Civil Engineering Department, Persian Gulf University, Mahini Street, Bushehr, Vaghefi@pgu.ac.ir

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ABSTRACT

Submerged breakwaters are a special type of breakwater associated with low wave reflection. They can also save large quantities of engineering resources from the view of economics. Although there have been previous investigations on the interaction between waves and rubble mound low-crested breakwaters, performance of impermeable submerged breakwater is somehow different from rubble mound structures. Thus, the accurate estimation of reflection and transmission coefficients is essential in designing of this kind of structures in near shore zone. In this paper, performance of impermeable trapezoidal submerged breakwater was investigated experimentally using regular waves. In the experimental plan, for three submergence depths of breakwaters different wave groups were used to measure transmission and reflection coefficients. Based on the test results, empirical expressions were formulated to describe the transmission and reflection coefficients for solid submerged breakwater under regular group waves.

1. Introduction

The coastal erosion as a worldwide problem endangers the coastal properties and causes degradation of valuable land and natural resources. It also disruption fishing, shipping and tourism industry [1]. Submerged breakwaters are used increasingly against the beach erosion and the coastal hazard by coastal engineers. These structures protect the shoreward area of the breakwater from wave actions by attenuating the incoming waves. Using of such constructions have multiple benefits such as coast erosion reduction, cheap coast constructions, overtopping reduction, force reduction and etc [2]. Although a submerged breakwater is locating across the beach, it does not interrupt the clear view of the sea from the beach. This is a desirable feature of these structures. This is one of the important considerations in using such structures for shore-line protection while maintaining the tourism value of beaches [3]. This structure causes the waves to break and dissipates some of the wave energy. Therefore

waves partly reflected and partly transmitted shoreward.

Wave transmission over submerged breakwaters have been studied in a series of works based on the laboratory and field experiments (e.g. Johnson et al.1951[4], Adams and Sonu 1986 [5], Van der Meer and Daemen 1994 [6], Losada et al., 1996 [7], D'Angremond et al., 1996 [8], Seabrook and Hall,1998 [9], Bleck and Oumeraci 2001 [10], Schlurmann et al. 2002 [11], Calabrese et al. 2002 [12], Hur et al., 2003 [13], Hur, 2004 [14], Cho et al., 2004 [15], Cox and Tajziehchi, 2005 [16], Van der Meer et al. 2005 [17], Jie et al., 2008 [18]).

As the numerical methods and wave models developed the past few decades, the modeling of wave transmission over submerged breakwaters and the criteria for the quality of the numerical model have become a challenge. So far, many theoretical or numerical models have been done for both the permeable and impermeable structures. Shen et al. (2004) developed a Reynolds-averaged Navier–Stokes

(RANS) model to predict the propagation of conical waves over a submerged bar [32]. Johnson et al. (2005) explained two methods for modeling waves and currents interactions with submerged breakwaters. The first method is a phase averaged method and the second approach is a phase resolving method [33]. Christou et al. (2008) studied the behavior of nonlinear regular waves interacting with rectangular submerged breakwaters based on a Boundary Element Method (BEM) [34]. Carevic et al. (2009) presented irregular waves transmission over submerged breakwater, using the numerical model MIKE 21 BW 1D [35]. Cao et al. (2010) presented a RANS model to predict water wave transmission over two impermeable trapezoidal submerged breakwaters. For this model, the $k-\varepsilon$ turbulence model and VOF surface tracking scheme were coupled with their solver [36]. Mahmoudi et al. (2013) simulated of wave propagation over a Submerged Breakwater on a Sloped Bed by WCSPH Method [37]. Hajivalie et al. (2015) investigated the effect of submerged vertical breakwater dimension on wave hydrodynamics and vortex generation around the breakwater with numerical modeling. In this numerical model, Reynolds Averaged Navier–Stokes (RANS) equations with a standard $k-\varepsilon$ turbulence closure model were implemented [38]. Yeganeh-Bakhtiary et al. (2017) presented a Numerical Study on Hydrodynamics of Standing Waves in Front of Caisson Breakwaters with WCSPH Model [39].

So far several empirical formulas for prediction of the wave transmission coefficient are available, but most of these formulas have been reported for rubble mound emerged structures. Nevertheless, limited studies have been reported empirical formulas for prediction of the wave transmission coefficient over submerged breakwaters (e.g. D'Angremond et al., 1996 [8], Bleck and Oumeraci, 2001 [10], Calabrese et al., 2002 [12], Cox and Tajziehchi, 2005 [16]).

Researches dedicated to wave reflection from coastal structures are fairly limited. Very often reflection is a byproduct of research on structure stability, wave overtopping or wave transmission. It means that a huge amount of data on reflection is available, but has only been used to establish the incident wave height in the model facility and has not been analyzed on its own. (e.g. Zanuttigh and Van der Meer, 2006 [19], Van der Meer et al., 2005 [17], Steendam et al, 2004 [20], Bruce et al. 2006 [21], Davidson et al., 1996 [22], Cappiotti et al., 2006 [23]).

So far several empirical formulae for the prediction of the wave reflection coefficient are available, but the most of these formulae have been reported for emerged low-crested structures and non-overtopped breakwater. (e.g. Seelig and Ahrens 1981 [24], Postma 1989 [25], Davidson et al. 1996 [22], Allsop and Hiettrarchi, 1989 [26], van der Meer et al., 2005 [17], Zanuttigh et al., 2008 [27]).

Nevertheless, the effect of a low-crest has been examined so far for rock permeable slopes only. Also For rock permeable low crested structures, the analysis was limited to design conditions under perpendicular wave attack. (e. g. Van der Meer et al., 2005 [17], Zanuttigh et al., 2008 [27]).

As mentioned above, the most of experimental works and empirical formulas for prediction of the wave transmission and reflection coefficient have been reported for low-crested structures of the rubble mound type. Sometimes smooth and impermeable structures exist, for example low-crested structures covered with asphalt or armored with a block revetment. Wave transmission over smooth low-crested structures is quite different from rubble mound structures. First of all, the wave transmission is larger for the same crest height, simply because there is no energy dissipation by friction and porosity of the structure. Furthermore, on the crest there is no energy dissipation, which is completely different from rubble mound structures. For only very wide (submerged) structures there could be some influence on the crest width, but this is not the case. The presence of tide makes it possible to construct these kinds of structures above water level. The problems associated with reflection of incoming waves from coastal structures and natural coasts are well recognized. They include dangerous sea states close to harbors entrances, influence on ship navigation in entrance channels. Furthermore they can intensify sediment scour, leading to dramatic loss in beach material and structure destabilization. It is expected that submerged structures will have smaller reflection than non-overtopped, due to the fact that more energy will go over the structure. It is also expected that the relative submergence depths h_s/H_i has the main influence on a possible reduction of the reflection coefficient. Furthermore, it is expected that reflection coefficient for impermeable submerged structures be more than rubble mound submerged breakwater.

In this research experimental tests were performed on impermeable submerged breakwaters under regular waves. Three different depths of submergence of breakwaters were selected during testing to obtain coefficients of transmission and reflection. An extensive scaling argument and regression analysis was carried out and some empirical equations were proposed to determine the transmission and reflection coefficients for impermeable submerged breakwaters. The results are expected to provide useful information with regard to predicting performance of impermeable submerged breakwaters under varying wave actions and varying submergences.

2. Experimental set up and Procedure

Experiments were carried out at the Hydraulics Laboratory, School of Engineering, Griffith University Gold Coast Campus. Fig. 1 shows the

experimental set-up of the impermeable submerged breakwater. Experiments were conducted in a glass wave flume with 8 m long, 0.5 m wide, and 0.8 m deep. A piston-type wave generator was used at one end of the flume, while an absorber system was installed at the other end to minimize the reflection from the beach. The wave absorber was made of sponge (see Fig. 1) with high efficiency and the type of wave maker was active. The submerged breakwater models were made of plywood with a trapezoidal shape. The toe of breakwater was placed at a distance of 4.4 m from the wave paddle. The size of submerged breakwater was 0.2 m crest wide, 0.2 m height and the front and the rear slope ratio were 1:2.

As illustrated in Fig. 1 three probes were fixed at the wave channel. Probes 1 and 2 were positioned in front of the submerged breakwaters to measure characteristics of the incident and reflected waves and Probes 3 and 4 were positioned in back of the submerged breakwaters to measure the transmitted wave characteristics. The distance between these two probes, denoted by Δl , is determined by the following limitations [28]:

$$0.05 \leq \Delta l / L \leq 0.45 \quad (1)$$

where L is wave length.

The location of probe 2 was selected as 1 m away from the breakwater and probe 3 was fixed 0.6 m away from the breakwater model at its lee side. The submerged breakwater model was subjected to the action of regular waves, of periods ranging from 1 sec to 1.6 sec at intervals of 0.1 sec. For each wave period, different wave heights ranging from 0.03 m to 0.14 m were generated. In these experimental work three water depths ($h = 0.25, 0.30, 0.35$ m) were used. Depending on the fluctuation in the flume, regular waves were generated over the models for 20–30 s.

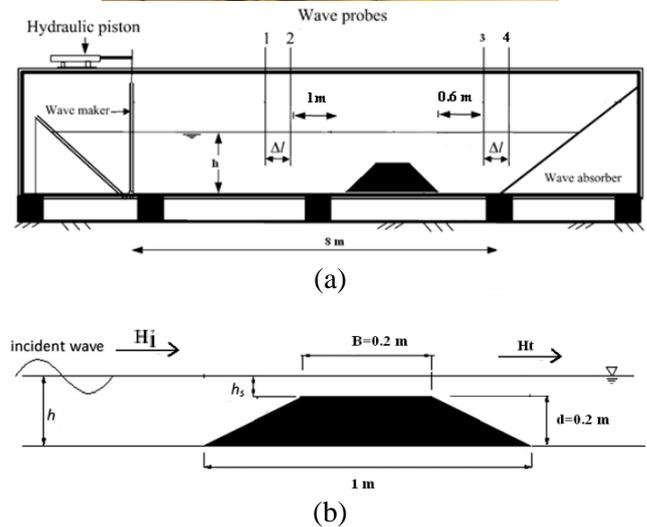


Fig. 1 Experimental set-up . a) Wave channel, b) Impermeable submerged breakwater.

3. Results and Discussions

Although few formulas on wave transmission exist, most of them developed on limited data sets. d'Angremond et al. (1996) [8] with as basis De Jong (1996) [29] came up with a formula for wave transmission on smooth structures as follows:

$$K_t = -0.4 \frac{h_s}{H_i} + \left(\frac{B}{H_i} \right)^{-0.31} \times [1 - \exp(-0.5\zeta)] \times 0.80 \quad (2)$$

in which transmission coefficient K_t is a number between 0.075 and 0.8. The formula for smooth structures is only based on a limited data set. h_s is the freeboard defined as the distance between the still water level and the structure crest level and $\zeta = \tan \alpha / \sqrt{2\pi H / gT^2}$ is Iribarren number where H is wave height, T is wave period and $\tan \alpha$ is front slope of structure. A negative value of freeboard represents a submerged structure case.

Van der Meer et al. (2000) tested smooth structures with different crest widths. He noticed that for smooth structures for a quite gentle seaward slope there was hardly any influence of crest width [31]. In their experimental work, all slopes were 1:4, both seaward and landward of the structure. A re-analysis was performed by Van der Meer et al. (2004) on all smooth structure data available and this led to the following equation to be used for 2D wave transmission at smooth low-crested structures:

$$K_t = -0.3 \frac{h_s}{H_i} + 0.75 [1 - \exp(-0.5\zeta)] \quad \text{for } \zeta < 3$$

$$K_t = -0.3 \frac{h_s}{H_i} + \left(\frac{B}{H_i} \right)^{-0.31} \times [1 - \exp(-0.5\zeta)] \times 0.75 \quad (3)$$

for $\zeta \geq 3$

which is valid for $0.075 \leq K_t \leq 0.8$

Bleck and Oumeraci (2001) have also experimentally investigated the wave transmission on impermeable submerged artificial reef with different heights and widths [10]. They presented the modified formula for impermeable submerged breakwater as:

$$K_t = 1 - 0.83 \exp\left(-0.72 \frac{h_s}{H_i}\right) \quad (4)$$

Cox and Tajziehchi (2005) have also experimentally investigated the wave transmission on impermeable submerged breakwater with different crest widths [16]. They presented the modified formula for impermeable submerged breakwater as:

$$K_t = 0.17 \frac{h_s}{H_i} + 2.84 \left(\frac{B}{H_i} \right)^{-0.26} \times [1 - \exp(-0.14\zeta)] \quad (5)$$

Eqs. (2) to (5) have been applied to the present experimental data, keeping in mind that the parameter ranges in experimental study are sometimes different from the ones investigated in the three original studies. It is obvious that if any formula is used outside the range in which it has been inferred, the accuracy of the estimations will decrease.

Fig. 2 shows the K_t calculated with the four formulae versus the measured one. The present experimental data are in average located above the line. Therefore a new analysis was performed on the data in order to come up with an improved formula for impermeable submerged breakwaters.

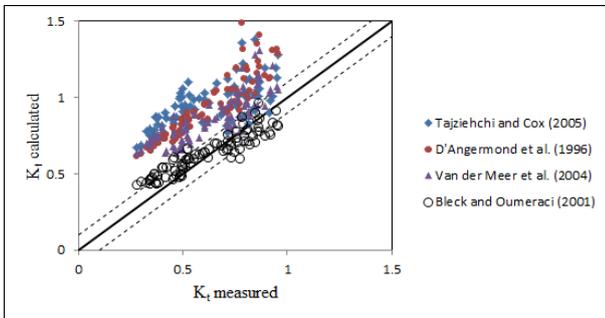


Fig. 2 Comparison between calculated and measured values of the transmission coefficient using the exiting Eqs. (2) to (5).

It is evident from Fig.2 that measured wave reflection is lower than the predicted ones. Therefore it is necessary to find a predictive tool to estimate the transmitted coefficient more accurately as an objective of this research.

Most reflection formulae are only valid for non-overtopped structures. It is expected that low-crested structures have smaller reflection than non-overtopped ones as more energy will pass over the low-crested structures. Furthermore, it is expected that reflection coefficient for smooth structures be more than rubble mound structures. One of the proposed equations was a modification to the previously proposed form of Battjes (1974), employing the surf similarity parameter as follows, [40]

$$K_r = 0.14\zeta^{0.73} \quad (6)$$

Seelig and Ahrens (1981) analyzed several data sets to introduce the following reflection coefficient parameterization:

$$K_r = \frac{a\zeta^2}{\zeta^2 + b} \quad (7)$$

The values of coefficients a and b depend on the structure type.

- for smooth slopes (e.g., beaches), $a=1.0$ and $b=5.5$
- for rough permeable slopes (e.g., rubble-mound), $a=0.6$ and $b=6.6$ [41]

For low-crested rubble mound breakwaters, Van der Meer et al. (2004) suggested an empirical equation for K_r as follow:

$$K_r = 0.14\zeta^{0.73} \left(0.2 \frac{h_s}{H} + 0.9 \right) \quad \text{for } \frac{h_s}{H} < 0.5$$

$$K_r = 0.14\zeta^{0.73} \quad \text{for } \frac{h_s}{H} \geq 0.5 \quad (8)$$

Wang et al. (2005) propose a new empirical equation to determine K_r for low-crested rubble mound structures as [30]:

$$K_r = 0.68 \frac{a\zeta^2}{\zeta^2 + b} \left(0.2 \frac{h_s}{H} + 0.9 \right) \quad \text{for } \frac{h_s}{H} < 0.5$$

$$K_r = 0.68 \frac{a\zeta^2}{\zeta^2 + b} \quad \text{for } 0.5 \leq \frac{h_s}{H} \leq 0.8 \quad (9)$$

where $a=0.1$ and $b=5.5$. The upper boundary is set as $h_s/H \leq 0.8$, which is the maximum value measured in the test.

Zanuttigh et al. (2008) proposed a new formula to predict the reflection coefficient K_r for rock permeable low-crested structures in design conditions as [27]:

$$K_r = \tanh(a\zeta^b) \times \left(0.67 + 0.37 \frac{h_s}{H} \right)$$

$$\text{for } -1 < \frac{h_s}{H} \leq 0.5 \quad (10)$$

where $a=0.12$ and $b=0.87$.

Zanuttigh and van der Meer (2008) proposed a new parameterization using a large database of over 4000

reflection coefficient values. Their new parameterization is given as

$$K_r = \tanh(a\zeta^b) \quad (11)$$

where the coefficients a and b have the following values:

- for smooth impermeable slopes: $a = 0.16$ and $b = 1.43$
- for permeable rubble-mound slopes: $a = 0.12$ and $b = 0.87$ [42]

Young and Testik (2011), Based on these experimental observations and scaling arguments, they propose the following two semi-empirical parameterizations for estimation of the reflection coefficient for normally incident waves to vertical (Eq.(12)) and semicircular(Eq.(13))submerged breakwaters[43].

$$K_r = 0.53 \exp(-.85 \frac{h_s}{H_i}) \quad (12)$$

$$K_r = 0.53 \exp(-1.4 \frac{h_s}{H_i}) \quad (13)$$

Eqs . (6) to (12) have been applied to the present experimental data, keeping in mind that the parameter ranges in experimental study are sometimes different from the ones investigated in the three original studies. It is obvious that if any formula is used outside the range in which it has been inferred, the accuracy of the estimations will decrease.

Fig. 3 shows the K_r calculated with the seven formulae versus the measured one.

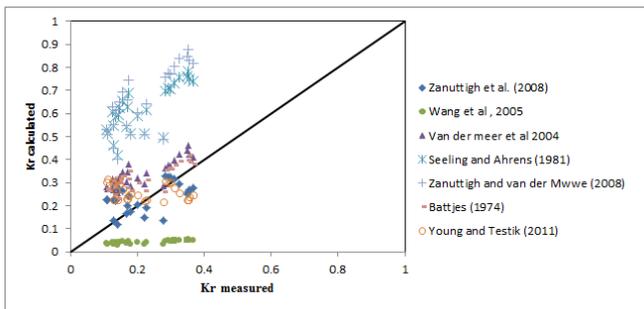


Fig. 3 Comparison between calculated and measured values of the reflection coefficient using the exiting Eqs. (6) to (12).

To the knowledge of authors, it seems that up to now there is no method available to predict the reflection coefficient for sloping impermeable submerged breakwater except for above equations as an approximate estimation.

In this paper, performance of the impermeable submerged breakwaters is evaluated using the transmission and reflection characteristics. The wave transmission properties of these breakwaters are defined by transmission coefficient, K_t . K_t is calculated as:

$$K_t = \frac{H_t}{H_i} \quad (14)$$

where H_i and H_t are incident and transmitted wave heights respectively.

The wave reflection coefficient, K_r , is used to define the wave reflection characteristics. K_r is obtained from:

$$K_r = \frac{H_r}{H_i} \quad (15)$$

where H_r is the reflected wave height. According to experimental conditions, the numerical procedure of Goda and Suzuki (1976) for regular waves was used to separate incident and reflected trains [28]. Once wave elevation data is collected, MATLAB codes are used for calculating incident wave heights and reflection coefficients. Incident wave heights are calculated by averaging the wave gage measurements from background tests. H_r is calculated by the reflection method of Goda and Suzuki (1976), which presupposes a superposition of multi-reflected waves within a testing environment, and resolves the components using the Fast Fourier Transform (FFT) technique. A complete explanation of this method and its calculations are demonstrated by Goda and Suzuki (1976) [28].

To perform a dimensional analysis considering the theoretical and experimental data, the following variables initially play a role in defining performance of impermeable submerged breakwaters and influence the wave transmission K_t (see Fig. 1(b)):

$$K_t = f(h_s, T, H_i, H_t, B, L_0, \tan \alpha) \quad (16)$$

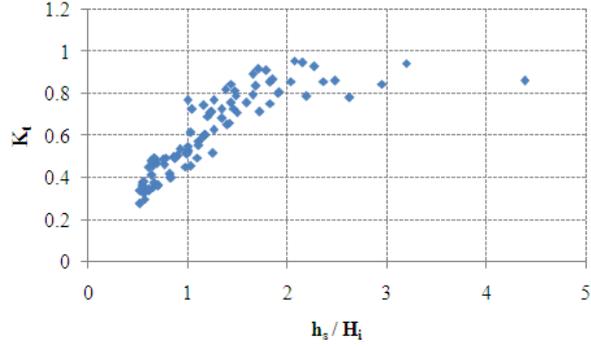
Expressing these parameters in non dimensional form we have:

$$K_t = f\left(\frac{h_s}{H_i}, \frac{B}{H_i}, \frac{L_0}{H_i}, \zeta\right) \quad (17)$$

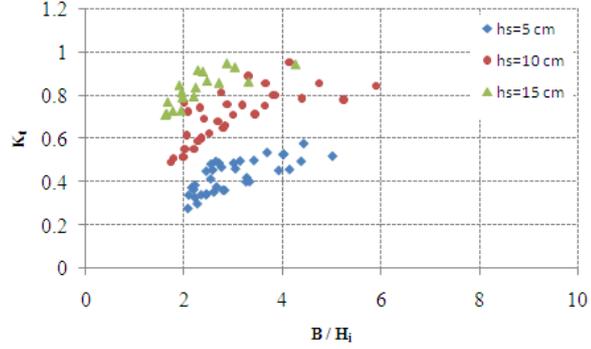
where $\zeta = \tan \alpha / \sqrt{2\pi H / gT^2}$ is Iribarren number. A qualitative parametric analysis was then performed to examine the effects of dimensionless variables on the wave transmission over impermeable submerged breakwaters. From the experimental observations made in the wave flume and examining Fig. 3 the following remarks can be drawn:

The variations in the transmission coefficient with dimensionless depth of submergence (h_s / H_i) are reported in Fig. 4 (a). This figure shows that the variation in the transmission coefficient increase with increase in the dimensionless depth of submergence. This is because probable of wave breaking decrease with increase in the dimensionless depth of submergence and decreasing the energy dissipation by wave breaking .

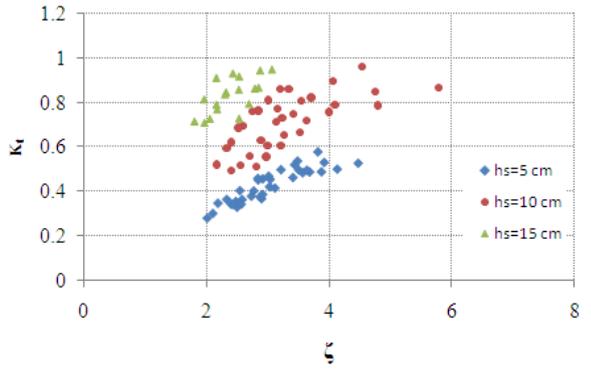
Fig. 4(c, d) shows the effects of L_0/H_i and Iribarren number (ζ) on performance of impermeable submerged breakwater. It is evident that the transmission coefficient increases as L_0/H_i and ζ increase. This is because with increasing the wave steepness (H_i/L_0) or in the other hands with decrease in L_0/H_i and ζ waves tend to break leading to increase in energy dissipation.



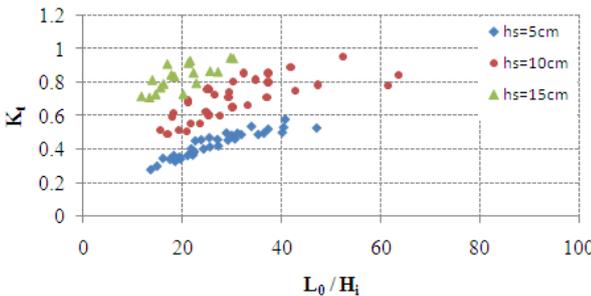
(a)



(b)



(c)



(d)

Fig. 4 Effects of dimensionless variables on the wave transmission through impermeable submerged breakwaters.

A multiple regression analysis was performed on the flume experimental data to determine the relationship between wave transmission and the independent variables. This can be used to develop an equation for estimating wave transmission through impermeable submerged breakwater. The proposed wave transmission equation was a proportional estimation between statistical validity and practical implication. It should be noted that some parameters, especially combined variables, may have statistical significance without any physical basis. Statistical analyses were performed to produce the best, simplest, and most feasible equation to assist with practical impermeable submerged breakwater design and evaluation.

Using the above data the following equation for wave transmission was found to provide a good representation of the wave transmission through impermeable submerged breakwater. Comparison between calculated and measured values of the transmission coefficient using the proposed formula is shown in Fig. 5. In this figure Dashed lines is 90% confidence interval and R^2 value is 0.76.

$$K_t = b_1 \left(\frac{h_s}{H_i} \right) + b_2 \left(\frac{B}{H_i} \right)^{b_3} \cdot (1 - \exp(b_4 \cdot \zeta))$$

$$b_1 = 0.272 \quad , \quad b_2 = 1.147 \quad , \quad b_3 = -0.971 \quad , \quad b_4 = -0.339 \quad (18)$$

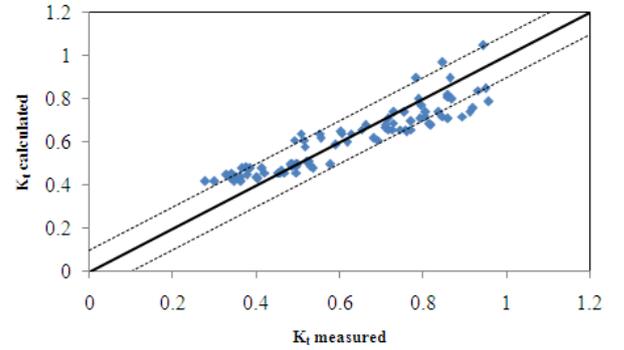


Fig. 5 Comparison between calculated and measured values of the transmission coefficient using the proposed formula.

The performance of impermeable submerged breakwater is also defined using the reflected waves. The reflection analysis is determined from the response of two wave probes installed in front of the structure. The reflection coefficient is calculated as the ratio of reflected and incident waves height as $K_r = H_r / H_i$.

The dimensional variables that influence the wave reflection (K_r) can be expressed as follow.

$$K_r = f(h_s, T, H_i, H_r, B, \tan \alpha) \quad (19)$$

The parameters of Eq. (13) were expressed as dimensionless forms by using π theory as:

$$K_r = f \left(\frac{h_s}{H_i}, \frac{B}{H_i}, \zeta \right) \quad (20)$$

From the work by Postma (1989) it is known that the wave period has more influence on the reflection behavior than the wave height [25]. Therefore the use of ζ introduces some scatter, but it also allows to

$$K_r = \frac{a \cdot \zeta^2}{b + \zeta^2} \cdot \left[c + d \frac{h_s}{H_i} \right] \quad (21)$$

$$a = 0.3, \quad b = 9.959, \quad c = 1.271, \quad d = 0.177$$

incorporate different slopes.

Zanuttigh et al. (2008) showed that the measured K_r to ζ ratio is only as function of the relative submergence depth h_s/H_i for rock permeable low crested structures, which is expected to have the most significant effect on wave reflection [27].

Fig. 6(a, b) shows effects of relative submergence depth h_s/H_i and Iribarren number (ζ) on performance of impermeable submerged breakwater, respectively. It is evident from Fig. 6(a) that the reflection coefficient decreases with increase in relative submergence depth h_s/H_i . This is because with increase in relative submergence depth, the wave transmission increases, leading to a decrease in reflection coefficient.

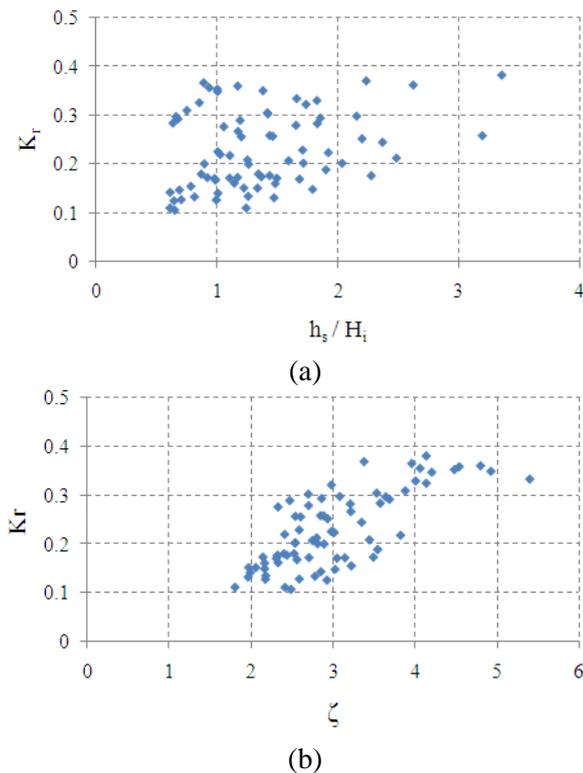


Fig.6 Influence of the relative submergence depth (h_s/H_i) and Iribarren number (ζ) on performance of impermeable submerged breakwater

In order to determine the relationship between wave reflection coefficient and the independent variables and to develop an equation for estimating wave reflection coefficient through impermeable submerged breakwater, statistical approach was used. The following equation for wave reflection coefficient was

then found to provide a good representation of the wave reflection coefficient through impermeable submerged breakwater. Comparison between calculated and measured values of the reflection coefficient using the proposed formula is shown in Fig. 7. In this Figure Dashed lines is 90% confidence interval and R^2 value is 0.62.

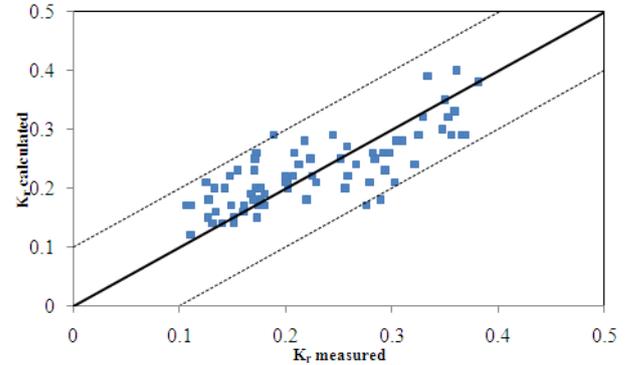


Fig.7 Comparison between calculated and measured values of the reflection coefficient using the proposed formula

4. Conclusions

In this research experimental investigations on permeable submerged breakwater was carried out in a laboratory flume. The experiments were performed using regular waves and three different submergence depths. In order to evaluate performance of impermeable submerged breakwaters, transmission and reflection coefficients were evaluated. The most important variables governing performance of impermeable submerged breakwaters were defined by using π theory and experimental results. These variables were obtained non dimensionally as $(h_s/H_i, B/H_i, \zeta)$ and $(h_s/H_i, \zeta)$ to determine K_t and K_r for impermeable submerged breakwater, respectively. Existing formulas were applied to the present experimental data. The results showed that, there is some deviation to predict K_t . Therefore a new analysis was performed on the present experimental data in order to come up with an improved formula for impermeable submerged breakwaters.

Finally in this study based upon new experimental data new empirical formulas are suggested to obtain transmission and reflection coefficients for impermeable submerged breakwater under regular waves. The empirically based equation developed has been shown to provide a good estimation of K_t and K_r for impermeable submerged breakwaters tested within the following range of parameters: $0.5 \leq h_s/H_i < 3$, $B/H_i < 6$, $\zeta \leq 6$.

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