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# A Study of Tsunami Reflection on Not-Armoured and Armoured Beach

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## ABSTRACT

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An experimental study has been carried out to investigate the tsunami reflection on not armoured and armoured beaches. The experiments were conducted in the glass-walled wave channel of 22.5 m length, 1.00 m width, and 0.50 m depth. First, natural beach material with a diameter of 0.35 mm and specific gravity of 2.63 was placed on 1/5 slope. Incident and reflecting wave heights were measured and the tsunami reflection coefficient ($H_r/H_i$) was calculated. Then, natural gravel and natural aggregate on diameters of 10 mm and 13.8 mm were placed the natural beach material throughout the slope, separately and each 5 cm thick, incident and reflecting wave heights were measured again, and reflection coefficients for these cases were calculated. These experiments, conducted with 1/5 slope, were repeated with 1 /2.5 and 1/6.5 slopes. In all slopes, armoured and not armoured surfaces, reflection coefficient decreases when dimensionless run-up height and dimensionless wave height increase. When slope increases, reflection coefficient increases too and when the diameter of armour unit increases, reflection coefficient decreases. After evaluation of the experimental results, the parameters that affect the tsunami reflection coefficient were determined. These parameters were written as a dimensionless group using Buckingham's Pi theorem. The regression analysis is carried out and empirical relationship is proposed. All experiments were repeated slope 1:3.5 for verification of the proposed relationship, and the results from this relationship and experimental results have been compared, and it was shown a good agreement between the results.

**ADDITIONAL INDEX WORDS:** *Reflection coefficient, Tsunami run-up height, Amour unit diameter*

## INTRODUCTION

Tsunamis are natural catastrophes resulting from landslides, collapses, and earthquakes. In offshore, tsunamis have low wave heights, tsunami wave lengths is very long compared with water depth. As they approach the shore, they get steep due to bathymetry, and reach high wave heights and caused human life and property losses in coastal areas. For example, Europeans first encountered with tsunami waves in 1755 Lisbon Earthquake which occurred in the Atlantic Ocean, and it led to the death of more than 50.000 people. The Indian Ocean Tsunami on 24 December 2004 affected 11 countries and caused 250.000 people death. For this reasons, many studies on reducing the tsunami risks were available in the literature. Tsunamis waves can be modelled as solitary waves (Liu, 1991; Synolakis (1986, 1987); Gedik *et al*., 2005) or N waves (Tadepalli and Synolakis, 1994, 1996). Hsiao *et al.* (2008) emphasized that solitary waves are often utilized to investigate the characteristics of tsunami behaviours because of their hydrodynamic similarities.

Various analytical and experimental studies for run-up of nonlinear waves on plane slopes were given by Pedersen and Gjevik (1983); Synolakis (1986, 1987); Synolakis and Skjelbreia (1993); Kanoglu and Synolakis (1998); Liu *et al.* (1991); Maiti and Sen (1999); Carrier *et al.* (2003); Teng *et al.* (2000); Shankar and Jayaratne (2003); Gedik *et al.* (2005). Nelemani *et al.* (1999) proposed simple empirical formulas to predict the pressures induced by regular waves on smooth, impermeable, sloped seawalls. They showed strong relations between wave reflection, wave run-up, wave run-down and phase shift of waves on wave pressures on the seawalls. Melito and Melby (2002) performed and experimental study to investigate the run-up and transmission response of a Core-Loc armour layer for irregular waves. Gedik *et al.* (2005) reported run-up height of tsunami on armored and not armored beaches Empirical formulas were suggested to be determined of tsunami run-up heights and coastal profile changes formed by tsunami. Also the relation between run-up height and erosion area was expressed with a formula. Gedik et al. (2006) investigated solitary wave run-down height and the geometric characteristics of solitary wave-induced strewing of armour units as experimentally and proposed empirical formulas. Many researchers are available in the literature about tsunami reflection. Cooker *et al.* (1997) considered the reflection at a vertical wall of a solitary wave, using a boundary-integral numerical code, a perturbation method, and re-analysis of cine film taken during the study by Maxworthy (1976). Silva *et al.* (2000) presented a linear solution for the interaction of tsunamis with coastal defence structures. Two types of coastal structures: an emerged porous breakwater and a submerged permeable or impermeable breakwater of arbitrary geometry are considered. The reflection and transmission coefficients are evaluated using the inverse Fourier transform. Chen *et al.* (2007) investigated propagation and reflection of internal solitary wave in a two-layer fluid as experimentally. Chang and Liou (2007) studied the reflection and transmission of long waves from a trapezoidal breakwater and a series of trapezoidal breakwaters, using the matching method. A systematic shape transfer is derived to determine wave reflection and transmission.

The purpose of this study is to investigate the tsunami reflection on armoured beaches experimentally and to propose empirical relationship by determining the effective parameters on the reflection coefficient.

# METHODS

## Experimental Set up

The experiments were conducted in the wave channel of the Hydraulic Laboratory of the ITU Faculty of Engineering, which is 22,5 meters long, 1,00 meter wide, and 0,50 meters deep. The side walls of the wave channel were made of glass to enable better observation of the experiments. A horizontal plate was placed in the wave channel, and this plate was connected to the pneumatic cylinder by a hinge. To initiate and stop the movement of the vertically placed pneumatic cylinder, a manual sliding valve was used. During the experiments, because the piston was not able to move the present mass of water instantly, accelerating exhausts and speed control valves were placed on the outlet and entry of the piston. To simulate the rapid movement in the sea bed, the piston attached to the horizontal plate was moved vertically, thus moving the mass of water, and generating the tsunami wave. Water surface elevations were measured using 4 resistance wave gauges. All of the wave gauges were calibrated prior to the experiment. First, natural beach material with a diameter of 0.35 mm and specific gravity of 2.63 was placed on 1/5 slope. Incident and reflecting wave heights were measured and the tsunami reflection coefficient ($H_r/H_i$) was calculated. Then, natural gravel and natural aggregate on diameters of 10 mm and 13.8 mm were placed the natural beach material throughout the slope, separately and each 5 cm thick, incident and reflecting wave heights were measured again, and reflection coefficients for these cases were calculated. These experiments, conducted with 1/5 slope, were repeated with 1/ 2.5 , 1/3.5 and 1/6.5 slopes as well.

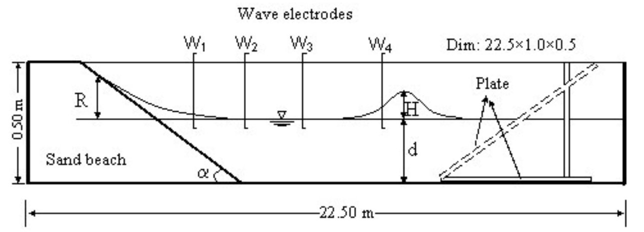


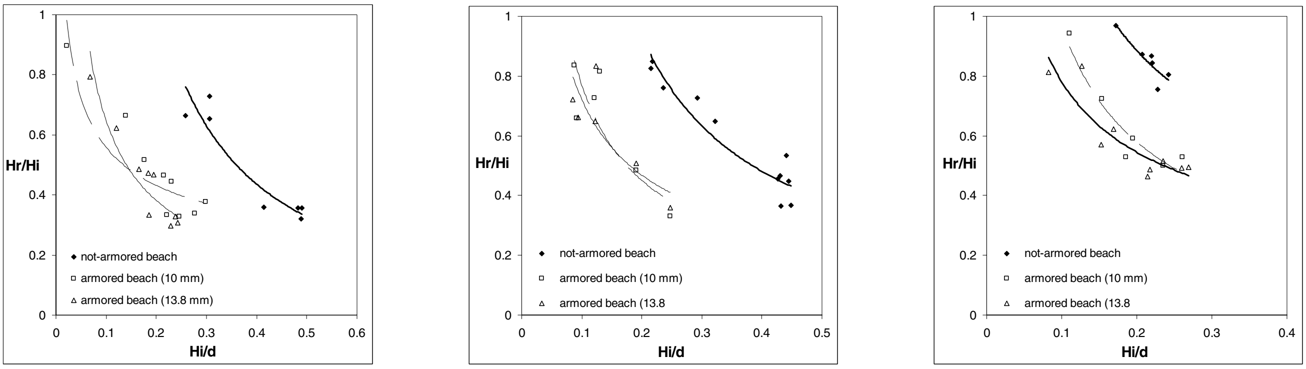
Figure 1. Experimental setup

# RESULTS

## Evaluation of Parameters Affected on Reflection

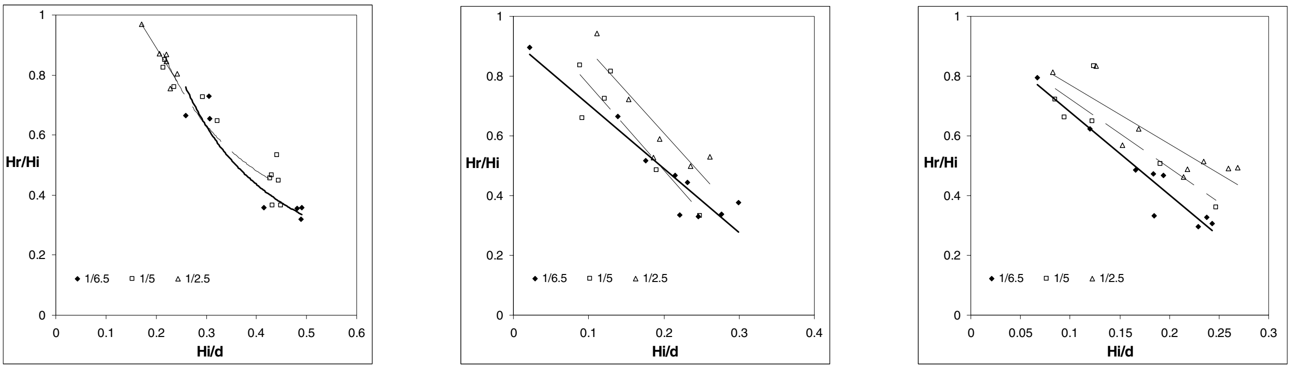
In this part, effects of slope, incedent and reflection wave height, run-up height and armour unit (with different diameter units) on reflection have been researched.

Figure 2 and 3 have been evaluated the effect of dimensionless incident wave height ($H_i/d$) on reflection coefficient according to each slope beaches that these beaches are placed not armoured and two different armoured units. It can be seen from these figures as dimensionless incident wave height increase, reflection coefficient decrease. In Table 1, reflection coefficient in a not armoured cases is approximately at the same value in a slope of 1/5 and 1/6.5 while this coefficient becomes higher in a slope of 1/2.5. Since run-up height decreases when slope increases, the amount of energy consumed during run-up also decreases and therefore reflection coefficient increases. Reflection coefficients of a armoured case are less then not armoured cases. Since armour units cause more wave energy consumption, reflection coefficient decreases accordingly.



(a) (b) (c)

Figure 2. Variation of reflection coefficients with dimensionless incident wave height on armoured and not-armoured cases a) 1/6.5 slope, b) 1/5 slope, c) 1/2.5 slope



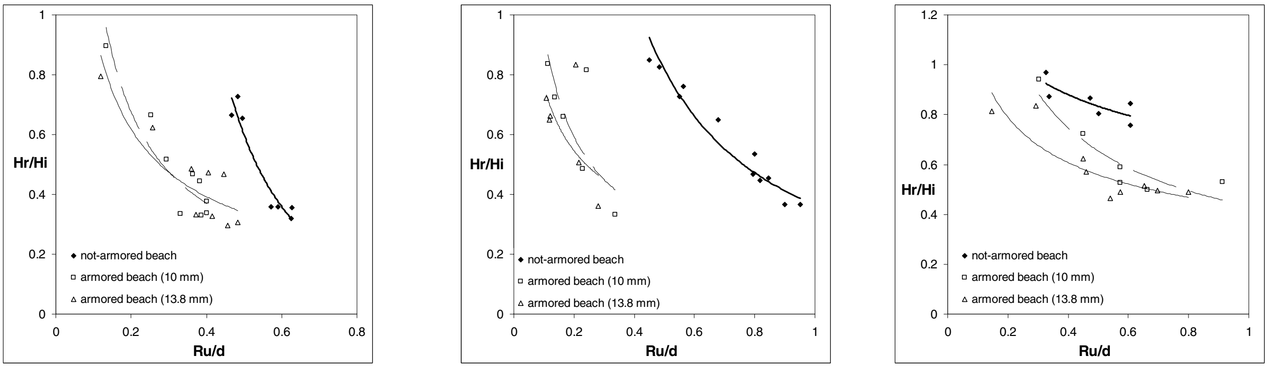
(a) (b) (c)

Figure 3. Variation of reflection coefficients with dimensionless incident wave height on different slopes a) not-armored, b) armoured case (10 mm) , c) armoured case (13.8 mm)

Table 1: Variation of reflection coefficients according to the dimensionless incident wave height on armoured and not-armoured cases

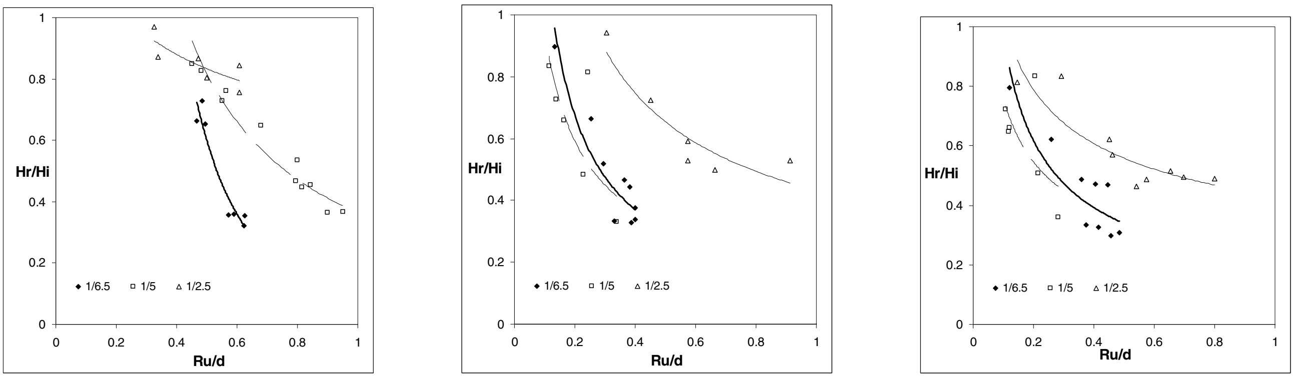
| | not armoured | | | armoured (10 mm) | | | armoured (13.8 mm) | | |
|---|---|---|---|---|---|---|---|---|---|
| Hi/d | $H_r/H_{i(1/6.5)}$ | $H_r/H_{i(1/5)}$ | $H_r/H_{i(1/2.5)}$ | $H_r/H_{i(1/6.5)}$ | $H_r/H_{i(1/5)}$ | $H_r/H_{i(1/2.5)}$ | $H_r/H_{i(1/6.5)}$ | $H_r/H_{i(1/5)}$ | $H_r/H_{i(1/2.5)}$ |
| 0.2 | - | 0.932 | 0.885 | 0.432 | 0.451 | 0.579 | 0.381 | 0.468 | 0.545 |
| 0.21 | - | 0.889 | 0.859 | 0.424 | 0.434 | 0.559 | 0.367 | 0.454 | 0.531 |
| 0.22 | - | 0.851 | 0.834 | 0.417 | 0.419 | 0.540 | 0.354 | 0.441 | 0.519 |
| 0.23 | 0.885 | 0.815 | 0.812 | 0.410 | 0.404 | 0.522 | 0.343 | 0.429 | 0.507 |
| 0.24 | 0.838 | 0.783 | 0.790 | 0.404 | 0.391 | 0.506 | 0.332 | 0.418 | 0.496 |
| 0.25 | 0.795 | 0.753 | 0.770 | 0.397 | 0.379 | 0.491 | 0.321 | 0.407 | 0.485 |
| 0.26 | 0.756 | 0.725 | 0.752 | 0.392 | 0.368 | 0.477 | 0.312 | 0.397 | 0.476 |
| 0.27 | 0.721 | 0.700 | 0.734 | 0.386 | 0.357 | 0.464 | 0.303 | 0.388 | 0.466 |
| 0.28 | 0.688 | 0.676 | 0.718 | 0.381 | 0.347 | 0.451 | 0.295 | 0.380 | 0.458 |
| 0.29 | 0.658 | 0.654 | 0.703 | 0.376 | 0.338 | 0.440 | 0.287 | 0.371 | 0.449 |
| 0.3 | 0.630 | 0.633 | 0.688 | 0.371 | 0.329 | 0.429 | 0.280 | 0.364 | 0.441 |

Figure 4 and 5 are presented as graphically the variation in the reflection coefficients for not-armoured and two different types of armour units with the variation in dimensionless run-up height (Ru/d) for each slopes. Reflection coefficient increases as run-up height increases (Table 2). When the slope in a not armoured cases increases, the ration between reflections coefficients also increase. However, reflection coefficient in a armoured case is approximately at the same value in a slope of 1/6.5 and 1/5 while this coefficient becomes higher in a slope of 1 /2.5. In both cases, since run-up height decreases in contrast with slope increment, the amount of energy consumed during run-up also decreases and therefore reflection coefficient increases. Reflection coefficients of a armoured case are less then not armoured cases.



(a) (b) (c)

Figure 4. Variation of reflection coefficients with dimensionless run-up height on armoured and not-armoured cases a) 1/6.5 slope, b) 1/5 slope, c) 1/2.5 slope



(a) (b) (c)

Fig. 5 Variation of reflection coefficients with dimensionless incident wave height on different slopes a) not-armored, b) armoured case (10 mm) , c) armoured case (13.8 mm)

Table 2: Variation of reflection coefficients according to the dimensionless run-up height on armoured and not-armoured cases

| Ru/d | not armoured | | | Ru/d | armoured (10 mm) | | | armoured (13.8 mm) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $H_r/H_{i(1/6.5)}$ | $H_r/H_{i(1/5)}$ | $H_r/H_{i(1/2.5)}$ | | $H_r/H_{i(1/6.5)}$ | $H_r/H_{i(1/5)}$ | $H_r/H_{i(1/2.5)}$ | $H_r/H_{i(1/6.5)}$ | $H_r/H_{i(1/5)}$ | $H_r/H_{i(1/2.5)}$ |
| 0.4 | - | - | 0.880 | 0.2 | 0.676 | 0.592 | - | 0.618 | 0.546 | 0.789 |
| 0.42 | - | - | 0.870 | 0.22 | 0.622 | 0.555 | - | 0.580 | 0.521 | 0.761 |
| 0.44 | - | - | 0.860 | 0.24 | 0.577 | 0.523 | - | 0.548 | 0.500 | 0.736 |
| 0.46 | 0.758 | 0.901 | 0.851 | 0.26 | 0.538 | 0.495 | 0.966 | 0.520 | 0.481 | 0.715 |
| 0.48 | 0.672 | 0.857 | 0.842 | 0.28 | 0.505 | 0.471 | 0.924 | 0.496 | 0.465 | 0.695 |
| 0.5 | 0.600 | 0.817 | 0.833 | 0.3 | 0.476 | 0.449 | 0.887 | 0.474 | 0.449 | 0.677 |
| 0.52 | 0.537 | 0.781 | 0.825 | 0.32 | 0.450 | 0.430 | 0.853 | 0.454 | 0.436 | 0.661 |
| 0.54 | 0.483 | 0.747 | 0.818 | 0.34 | 0.427 | 0.413 | 0.823 | 0.436 | 0.423 | 0.646 |
| 0.56 | 0.436 | 0.716 | 0.811 | 0.36 | 0.406 | 0.397 | 0.796 | 0.420 | 0.412 | 0.632 |
| 0.58 | 0.395 | 0.687 | 0.804 | 0.38 | 0.387 | 0.383 | 0.770 | 0.406 | 0.401 | 0.619 |
| 0.6 | 0.359 | 0.661 | 0.797 | 0.4 | 0.371 | 0.370 | 0.747 | 0.392 | 0.392 | 0.608 |

## Dimensionless Parameters

The dependent variables for reflection coefficients have been determined as a result of experimental evaluations: incident wave height ($H_i$), reflecting wave height ($H_r$), water depth in the constant depth region (d), run-up height (Ru), water density ($\gamma_w$), sand density ($\gamma_s$), armor unit diameter ($D_{n50}$), the angle of the slope ($\beta$), and the acceleration of gravity (g). Writing this as an expression in functional form:

$$f(H_i, H_r, d, Ru, \gamma_w, \gamma_s, D_{n50}, \beta, g) = 0 \qquad (1)$$

Dimensionless parameters are obtained by using Buchingam theory for choosing the variables d, $\gamma_s$ and g as the independent physical variables, as follows;

$$f\left(\frac{H_i}{d}, \frac{H_r}{d}, \frac{Ru}{d}, \frac{\gamma_s}{\gamma_w}, \frac{D_{n50}}{d}, \tan\beta\right) = 0 \qquad (2)$$

where $H_i/d$ is dimensionless incident wave height, $H_r/d$ is dimensionless reflecting wave height, Ru/d is dimensionless run-up height, $G_{sb} = \gamma_s / \gamma_w$ is specific gravity of sand, $D_{n50}/d$ is dimensionless diameter of sand and $\tan\beta$ is dimensionless slope angle.

## Proposed Relationship for Tsunami Reflection Coefficient

A dimensionless group that includes the dimensionless parameters referred to as par1 (Eq. 3).

$$par1 = \left(\frac{d}{Ru}\frac{d}{D_{n50}}\frac{\gamma_s}{\gamma_w}\tan\alpha\right) \qquad (3)$$

The proposed relationship (Eq. 4) is determined by using Eq. 3 and regression analysis (Figure 6). The correlation coefficient is 0.85.

$$\frac{H_r}{H_i} = 0.4629\,par1^{0.467} \qquad (4)$$

The experiments have been repeated a slope 1:3.5 for verification of the proposed equation. The obtained measurement results from these experiments are substituted in Eq. 4, and reflection coefficients have been calculated. In Figure 7, the results obtained from proposed equation have been compared with measurement results. It has been observed that there is a good agreement between the measured and calculated reflection coefficients.

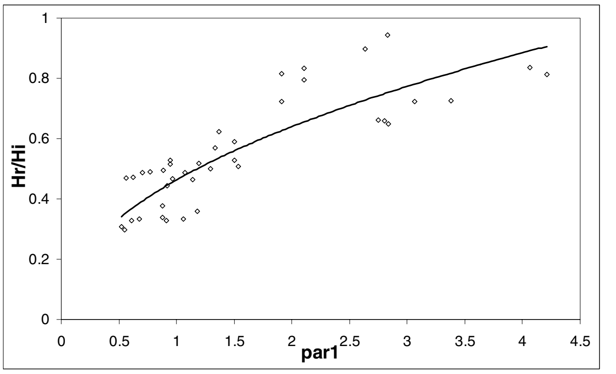


Figure 6. Variation of reflection coefficients with par 1

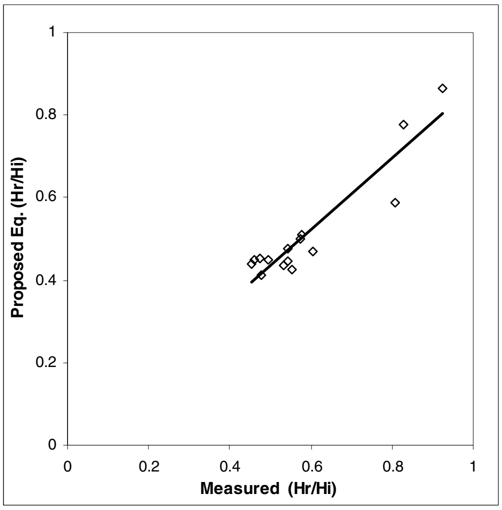


Figure 7. Comparison of proposed (Eq. 4) and measured reflection coefficients for armoured beach

## CONCLUSIONS

In this study, tsunami reflections on not armoured and armoured beaches are investigated as experimentally. Change of reflection coefficient with dimensionless incedent wave height and dimensionless run-up height has been examined in different slopes for not armoured and armoured cases. Reflection coefficient in a not armoured case is approximately at the same value in a slope of 1/5 and 1/6.5 while this coefficient becomes higher in a slope of 1 /2.5 (Figure 3a).

In all slopes, armoured and not armoured surfaces, reflection coefficient decreases when dimensionless run-up height and dimensionless wave height increase. When slope increases, reflection coefficient increases too and when the diameter of armour unit increases, reflection coefficient decreases. This is because coarser armour unit reduces wave energy due to turbulence and friction. Regarding this knowledge and using dimensionless parameters which are effective on reflection coefficient, Eq. 4 has been proposed. Reflection coefficient obtained from measurement results of this experiment and reflection coefficients obtained from Eq. 4 have been compared in Figure 7. It has been observed that there is a good agreement between the measured and calculated reflection coefficients.

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