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Excess energy approach for wave energy dissipation at submerged structures

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ABSTRACT

Using the excess energy approach, it is found that the net energy dissipation rate on submerged structures can be defined in terms of submerged depth, transmission coefficient and transmitted wave height. In order to generate a definition for the net energy dissipation on submerged structures, the difference between the wave energy dissipation rates per unit volume at break and the wave energy dissipation rate during the wave transformation is incorporated. The analytical solution is tested by laboratory study and the computed solutions are validated with the results of previously published studies. Based on laboratory results an empirical relationship representing the wave transmission coefficient is also proposed based on spilling and plunging type of breaks. Both the relations were linear and were defined in terms of relative submergence parameter and wave steepness parameter. The dominant effect of plunging type of breaks on wave energy dissipation rates is validated for submerged structures while smaller effect of spilling type of break is approved. It is shown that the proposed definition for energy dissipation is robust and accurate, and can easily demonstrate the net energy dissipation rates at submerged structures.

1. Introduction

Natural or artificial submerged structures are generally defined as a shore detached structures parallel to the shoreline. They are generally reducing the energy of propagating waves by a compulsorily breaking process. Artificial submerged structures are widely used to develop man-made beach profiles by generating sheltered areas while protecting erosion of coastal areas. Lately, they are also used to enhance aquatic habitats by causing more stable areas within the dynamic, unstable coastal environments such as ball reefs (Armono, 2003).

Knowledge of wave energy dissipation over a submerged structure, and wave transmission represents a major substantial practical concern for short and long term changes in coastal hydrodynamics. Wave energy reduction as the wave passes over the submerged structure is caused by inducing wave breaking. The wave height at the offshore side of the structure decreases slightly due to the energy dissipation and reaches a minimum value at the near shore edge. A performance characteristic of energy dissipation on submerged structures is previously studied in laboratory model tests by Ahrens and Fulford (1988) and Kabdaşlı and Türker (2002). Their tests showed that due to submerged structures 17–50% of the wave energy is dissipating. Gu and Wang (1992) developed a boundary equation model to simulate the wave energy dissipation within submerged breakwaters. Ting et al. (2004) studied the effects of porosity of submerged structures on wave energy losses during wave attenuation over the structures. Mendez et al. (2001) formulated the energy dissipation by breaking on submerged structures in which mass flux, energy flux, radiation stress and mean water level were analyzed for this purpose. Tsai et al. (2006) on the other hand worked out a numerical model based on time dependent mild slope equation to investigate the wave transformation over the submerged structures.

There are many studies analyzing wave decay after the wave breaking phenomena. Usually, these studies are based on two different approaches. These approaches are mainly differing from each other by means of their formulization. One of these approaches is derived for random waves and energy dissipation relationship is developed based on a turbulent bore which yields wave heights and set up through the surf zone as in Battjes and Janssen (1978) and Battjes (1986). The second approach is modeled by Dally et al. (1984), which is originally developed for monochromatic waves. The model is called excess-energy (EE) approach. This approach is then modified to simulate transformation of random waves (Kamphuis, 1991) by using a wave-by-wave approach (Dally, 1992). The model proposed by Dally et al. (1984) has been verified extensively for a variety of wave conditions, including laboratory and field conditions and monochromatic and random waves.

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As a result of wave decay on submerged structures, a ratio between the wave height before and after the wave break can be defined in terms of the transmissivity property of submerged structure. The transmissivity is therefore can be defined as a function of structure's geometric characteristics and wave parameters. The structure transmissivity is generally represented by the transmission coefficient and hence, this coefficient is a dimensionless ratio between the wave heights at offshore and onshore sides of submerged structure.

It is clear from the examination of the literature that among the geometric characteristics and wave parameters, empirical definition of transmission coefficient is highly dependent upon the submerged depth and incoming wave height (D'Angremond et al., 1996; Buccino and Calabrese, 2007). The other significant variables in the empirical equations employed to define transmission coefficient are the crest width, mean armor diameter of the submerged structure and wave length and period. These variables are successfully used to investigate the physical effects of submerged structures on coastal dynamics. Ting et al. (2004) considered the role of structure porosity and depicted that the porosity of the permeable structure reduces the effect of the transmission coefficient. Rao et al. (2009) conducted physical model studies in a monochromatic wave flume to evaluate the wave transmission characteristics of a submerged plate breakwater consisting of a fixed plate. Later, the transmission coefficient on submerged poro-elastic structures were theoretically analyzed by Lan and Lee (2010), based on linear wave theory.

In this paper, an attempt is made to develop a simple expression to predict the net energy loss at artificial submerged structures based on excess energy approach. The modification of the wave energy flux at the offshore side of the submerged structures is used in corporation with the energy flux at the nearshore region. Thus, the net energy dissipation while the wave passes over the submerged structure is evaluated. The analysis is focused on the relative importance of wave dissipation and wave transmission at the structure. The study also includes the analysis of changes in transmission coefficient in terms of spilling and plunging type of wave breaks over the submerged structures.

2. Wave energy dissipation model

The construction purpose of submerged breakwater is to dissipate the energy of waves by a compulsory break and requires a detailed experimental and analytical investigation. The general aim herein, is to adapt an existing wave breaking model to adequately simulate wave energy dissipation rate on submerged structures. The approach is based on Dally et al. (1984) model which is well known as Excess Energy (EE) model. The energy balance equation for waves advancing directly toward shore is based on the steady state equation.

$$\frac{\partial}{\partial x}(P\cos\theta)+\frac{\partial}{\partial y}(P\sin\theta)=D(x,y) \quad (1)$$

where $D(x,y)$ is the energy dissipation rate per unit surface area due to wave breaking, turbulence, etc., x and y are cross-shore and longshore coordinates respectively, P is the wave energy flux and θ is the angle between the wave orthogonal and bottom contours. The model assumes that the wave propagates at a gentle slope such that the breaking starts at the point where the bottom becomes horizontal. Wave breaking does not stop instantaneously over the horizontal surface and continue until stable wave height is attained. Therefore, the rate of wave energy dissipation per unit of horizontal area $D(x,y)$, used in Eq. (1) is given to be proportional to the difference between the local wave flux and the stable wave flux. The assumption that the wave conditions are uniform alongshore simplifies the Eq. (1) into:

$$D=\frac{\partial}{\partial x}(P\cos\theta)=\frac{K_d}{h}(P-P_s) \quad (2)$$

K_d is empirical wave decay coefficient and h is mean water depth. The wave decay coefficient controls the rate of energy dissipation, whereas the stable energy flux determines the amount of energy dissipation necessary for stable conditions to occur once breaking is initiated. Thus stable wave conditions refer to a state in which the effect of energy dissipation during breaking ceases, allowing waves to reform. Stable wave height is a function of water depth.

$$H_{st}=\Gamma h \quad (3)$$

where H_{st} is the stable wave height and Γ is the stable wave height coefficient. Dally et al. (1984) recommended $K_d=0.15$ and $\Gamma=0.40$. The wave energy flux per unit length of wave crest or, equivalently, the rate at which wave energy is transmitted across a plane of unit width perpendicular to the direction of wave advance, is the product of the wave energy, and the wave group speed.

$$P=EC_g \quad (4)$$

where E is the wave energy density and C_g is wave group speed. The wave energy density, which consists of two parts, potential and kinetic, is given as;

$$E=\frac{1}{8}\rho gH^2 \quad (5)$$

where ρ is the density of water and H is the wave height. Further, by using the shallow water wave group speed definition and rewriting Eq. (4) in terms of wave energy and wave group speed, the energy flux attained as the wave breaks can be expressed as follows

$$P_{wave}=EC_g=\frac{1}{8}\rho gH_i^2(gh_b)^{1/2} \quad (6)$$

which is the product of wave energy density and group velocity at break. The broken waves, after some time recovers itself back to a stable stage. At this time the net energy flux of the wave is

$$P_{stable}=E_sC_g=\frac{1}{8}\rho g(\Gamma h)^2(gh)^{1/2} \quad (7)$$

The difference between the stable wave energy flux and the energy flux attained as the wave breaks ($P_{wave}-P_{stable}$) yields the net energy flux dissipated on the submerged structure. Considering that the wave breaking phenomenon took place at the same depth where the wave recovers itself (Dally et al., 1984), the net energy flux dissipated is the difference between the stable wave energy flux and energy flux attained as the wave breaks. The net energy flux can be defined as

$$P_{net}=\frac{1}{8}\rho g^{3/2}[H_i^2h^{1/2}-\Gamma^2h^{5/2}] \quad (8)$$

Then, the wave energy dissipation per unit of volume can be obtained by substituting Eq. (8) into Eq. (2) with the assumption that bottom contours in front of the submerged structure are parallel and are perpendicular to the structure;

$$D_{net}=\frac{1}{h}\frac{\partial P}{\partial x}=\frac{K_d}{8h^2}\rho g^{3/2}[H_i^2h^{1/2}-\Gamma^2h^{5/2}] \quad (9)$$

where x is the onshore-offshore direction. Wave energy dissipation models have been already used in the literature for sediment transport analyzes and beach profile predictions (Kriebel et al., 1991; Hanson, 1992; Larson and Kraus, 1989; Larson et al., 1990). In most of these studies and in many others (Kriebel and Dean, 1985; Türker and Kabdasli, 2004; Cho and Kim, 2008) D_{net} is defined as wave energy dissipation per unit volume. However, the unit of the Eq. (9) is showing that D_{net} is actually reflecting the wave power