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Study on slamming pressure calculation formula of plunging breaking wave on sloping sea dike

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Abstract

Plunging breaker slamming pressures on vertical or sloping sea dikes are one of the most severe and dangerous loads that sea dike structures can suffer. Many studies have investigated the impact forces caused by breaking waves for maritime structures including sea dikes and most predictions of the breaker forces are based on empirical or semi-empirical formulae calibrated from laboratory experiments. However, the wave breaking mechanism is complex and more research efforts are still needed to improve the accuracy in predicting breaker forces. This study proposes a semi-empirical formula, which is based on impulse—momentum relation, to calculate the slamming pressure due to plunging wave breaking on a sloping sea dike. Compared with some measured slamming pressure data in two literature, the calculation results by the new formula show reasonable agreements. Also, by analysing probability distribution function of wave heights, the proposed formula can be converted into a probabilistic expression form for convenience only.

Keywords: Plunging breaker; Slamming pressure; Sea dike; Semi-empirical formula; Probabilistic expression

1. Introduction

In the low-lying coastal regions, sea dikes designed with the objective of managing shoreline erosion and preventing flooding from the sea (Murphy et al., 2002), are usually the most common and important coastal defense structures. Wave breaking on a sea dike slope is one of the most important problems for the coastal engineers to be investigated. It is well known that breaking types on sea dikes include spilling breaker, plunging breaker and surging breaker. Plunging breaker is the most dramatic wave breaking phenomenon in which the wave curls over and the wave energy is dissipated over a short distance and within a short time, which results in a high slamming pressure on sea dike slope. Therefore, slamming pressure due to plunging wave breaking is one of the main loads of sloping sea dikes, which may lead to failures of sea dikes under extreme waves.

However wave breaking is a complex phenomenon which is not yet fully understood (Liiv, 2001), especially in the roller and splashing regions where high intensity air bubbles are entrained (Kiger and Duncan, 2012; Lim et al., 2015). So, most of the research works on the slamming pressure on sea dikes or other coastal structures, like piles, are based on the laboratory experiments or field investigations (Endresen and Tørum, 1992; Ru and Li, 2002; Wienke and Oumeraci, 2005; Ren and Wang, 2005; Stagonas et al., 2012). In recent decades, a growing number of studies have focused on the dynamics and kinematics of wave breaking based on numerical simulation (Iafrati and Campana, 2003; Kotoura et al., 2010; Jiang et al., 2011; Risov and Voronovich, 2011; Zhang et al., 2014; Makris et al., 2016). The following review will mainly focus on slamming pressure on coastal structures due to plunging wave breaking.

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1.1. Morison formula

Morison formula (Morison et al., 1950) has been widely used for calculating wave loads on submerged structures (Stanivuk et al., 2014). It is based on the assumption that the wave force can be given by the linear superposition of a drag force which is dependent on the square of the water particle velocity and the submerged structure's projected frontal area, and an inertia force which is dependent on the acceleration of the water particle and the submerged structure's volumetric displacement. For example, the wave force per unit length experienced by a slender cylinder is expressed in the Morison formula as (Avila and Adamowski, 2011; Boccotti et al., 2013; Zhang et al., 2015):

$$F = F_d + F_m = \frac{1}{2}\rho_w C_d D u|u| + \rho_w C_m \frac{\pi D^2}{4}\frac{\partial u}{\partial t} \tag{1}$$

where F_d is the drag force; F_m is the inertia force; C_d is the drag coefficient; C_m is the inertia coefficient; ρ_w is the water density; D is the diameter of the cylinder; u is the water particle velocity; t is the time. Usually, it is essential to carry on the hydrodynamic experiment so as to determine the value of C_d and C_m.

When the cylinder comes to breaking wave attack, an additional slamming force of short duration because of the impact of the breaker front and the breaker tongue has to be considered. So, an additional slamming force (F_s) has to be added to the Morison formula as:

$$F = F_d + F_m + F_s \tag{2}$$

The slamming force F_s per unit length is given by the following equation (Chella et al., 2012; Rausa et al., 2015):

$$F_s = \frac{1}{2}\rho_w C_s D u^2 \tag{3}$$

where C_s is the slamming coefficient which is one of the most investigated parameters related to the slamming forces, and for different researches it has been ranged from π−2π.

1.2. Führböter and Sparboom formula

As already stated by Führböter (1986), the maximum slamming pressure (p_{max}) due to breaking waves acting on sea dike slope is a stochastic variable even for regular waves because the instabilities at the breaking point are influenced by the highly turbulent water−air mixture produced by the preceding breakers, and it follows a Log-Normal distribution. Some test series using regular waves were carried out in the 1:10 model and in the prototype, and the relationship between the incoming wave height H and the resulting impact pressures was expressed by:

$$p_{\max} = p_i = const_i \rho_w g H \tag{4}$$

where i = 50, 90, 99, 99.9% etc (which represent the probability); H = incoming wave height at the dike toe; p_i = the maximum pressure that is not exceeded in i % of the cases. In 1988, Führböter and Sparboom proposed an improved empirical equation which contains the influence of the dike slope angle:

$$p_{\max} = p_i = const_i \rho_w g H \tan(\alpha) \tag{5}$$

where i = 50, 90, 99, 99.9%, and the corresponding $const_i$ = 12, 16, 20, 24; α = dike slope angle.

Eq. (5) did not take into account the influence of the wave steepness on the maximum pressure. This drawback can be eliminated using an empirical function k_i that depends on the wave steepness instead of the constant value $const_i$. The modified equation proposed by Stanczak (2009) was given as:

$$p_{\max} = p_i = k_i \rho_w g H \tan(\alpha) \tag{6}$$

with $k_{50} = -289\frac{H}{gT^2} + 11.2$

where i = 90, 99, 99.9%, and the corresponding k_{90} = 1.33 k_{50}, k_{99} = 1.67 k_{50}, $k_{99.9}$ = 2.5 k_{50}; T = wave period.

1.3. Ikeno et al. formula

Tanimoto et al. (1984) performed large-scale experiment on an upright breakwater using a sine wave, and proposed formula to estimate wave pressures as follows.

$$\begin{cases} p_m(z)/\rho_w gH = 2.2(1 - z/3H) & (0 \le z/H \le 3) \\ p_m(z)/\rho_w gH = 2.2 & (z/H \le 0) \end{cases} \tag{7}$$

where p_m is the maximum wave pressure; z is the height from the still water level.

Eq. (7) did not take into account the influence of the wave breaking on the maximum pressure. So, Ikeno et al. (2001) introduced the extra coefficient σ for wave breaking into Eq. (7):

$$\begin{cases} p_m(z)/\rho_w gH = 2.2(1 - z/3H)\sigma & (0 \le z/H \le 3) \\ p_m(z)/\rho_w gH = 2.2\sigma & (z/H \le 0) \\ \sigma = 1.36 & 0 \le z/H \le 3 \\ \sigma = 1.36(1 + 0.52z/H) & (-0.5 \le z/H \le 0) \\ \sigma = 1.0 & (z/H \le -0.5) \end{cases} \tag{8}$$

In 2003, Ikeno and Tanaka further modified Eq. (8):

$$\begin{cases} p_m(z)/\rho gH = 3 - z/H & (0.5 \le z/H \le 3) \\ p_m(z)/\rho gH = 4 - 3z/H & (0 \le z/H \le 0.5) \\ p_m(z)/\rho gH = 4 + 3.6z/H & (-0.5 \le z/H \le 0) \\ p_m(z)/\rho gH = 2.2 & (z/H \le -0.5) \end{cases} \tag{9}$$

Note that this formula suggests that the maximum pressure load occurs near the still water level, i.e., $p_{\max} = 4\rho gH$ (z/H = 0, where z = 0). The Laboratory data of Lin et al. (2012) suggested that Eq. (9) was reliable.

1.4. Aims of this study

Results from previous studies mentioned above have shown a wide range of breaking wave impact loads measured or