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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.

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

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):

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

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

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

Note that this formula suggests that the maximum pressure load occurs near the still water level, i.e., $p_{\max} = 4\rho g H$ (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 calculated on coastal structures, but it is still very difficult to estimate exactly these loads numerically or empirically. Until now, some efforts (Boccotti et al., 2012, 2013; Naghipour and Morteza., 1996; Zhang et al., 2015) are still made aiming to explore the accuracy improvement issues in predicting wave impact forces.

The aims of this paper are to review the published literature, to propose a semi-empirical formula for estimation of the slamming pressure, and to compare the measured slamming pressures with the predicted results from the proposed semi-empirical formula. With these aims, first a review of the literature is presented, then the proposed formula is described in detail, and, finally, results are summarized and discussed.

2. Semi-empirical formula

In this section, we propose a semi-empirical formula for the estimation of the slamming pressure due to wave breaking on a sea dike slope. In Fig. 1 the principle sketch of wave breaking on a dike slope and the control volume for analysis of the slamming pressure are given. The establishment of the semi-empirical equation is based on the following simplified assumptions:

(1) The fluid is incompressible.
(2) On the control volume, the gravity force and dynamic pressures of sections 1–1 and 2–2 are considered negligible.

Applying impulse–momentum relation in y direction between sections 1–1, 2–2 and 3–3, the slamming force F_y on the control volume can be written as:

$$F_y = \rho Q(\beta_2|u_2|\sin\alpha_1 + \beta_1|u_1|\sin\alpha_2) \tag{10}$$

where the force F_y depends on the discharge Q and the velocity u. The factor β describes the inhomogeneous distribution of the velocity. For a homogeneous velocity distribution the factor is set to 1. Let $u_2 = u_1 = u$ and $Q = uA$ (A is section area), this gives:

$$\begin{aligned} &F_y = \rho u^2 A(\sin\alpha_1 + \sin\alpha_2) \\ &\Rightarrow F_y/A = p_y \le 2\rho u^2 \end{aligned} \tag{11}$$

where p_y is the slamming pressure on the sea dike slope.

The velocity u is predicted by the energy-balance equation which can be expressed as:

$$\frac{1}{2}\Delta m u^2 = E_k + E_p \tag{12}$$

with $E_p = \Delta m g \eta_b$

where $\Delta m u^2/2$ is kinetic energy of the water particle at section 1–1 location; Δm is the water particle mass; E_k and E_p present the water particle kinetic energy and potential energy at the breaking wave crest location, respectively; η_b is the maximum free surface height from the still water level at the breaking location.

The wave breaks when the water particle velocity at the wave crest exceeds the wave celerity. In shallow water, wave celerity (u_w) is proportional to the square root of water depth (h), i.e. $u_w = \sqrt{gh}$. Assume that the water particle velocity (u_b) at the breaking wave crest is equal to the wave celerity, then:

$$E_k = \frac{1}{2}\Delta m u_b^2 \approx \frac{1}{2}\Delta m g d_b \tag{13}$$

where d_b is the water depth at the breaking location. Using Eq. (13), the energy-balance equation becomes:

$$\begin{aligned} &\frac{1}{2}\Delta m u^2 = \frac{1}{2}\Delta m g d_b + \Delta m g \eta_b \\ &\Rightarrow u = \sqrt{g(d_b + 2\eta_b)} \end{aligned} \tag{14}$$

According to experimental data of Lin et al. (2012), $\eta_b \approx 0.8\ H_b$ (where H_b is the breaking wave height at the breaking location). Thus, the worst case of a plunging breaker can be modelled as follows:

$$p_y = 2\rho g(d_b + 1.6H_b) \tag{15}$$

It is assumed that the breaking wave height is related to a constant ratio of the water depth at the breaking location, i.e.

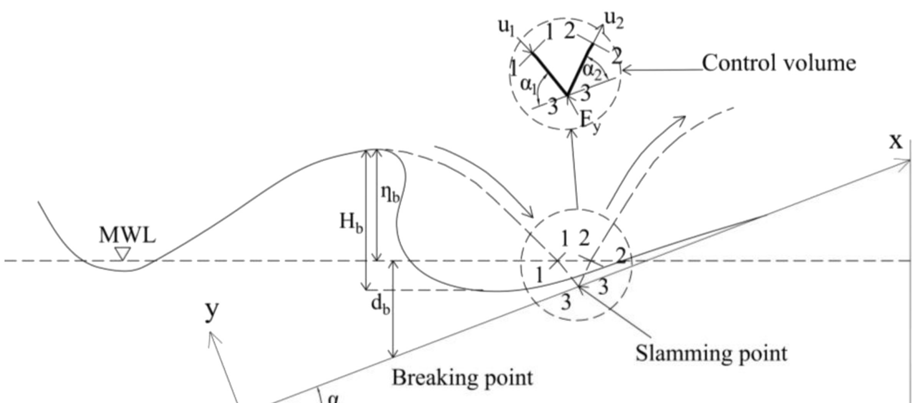

Fig. 1. Wave breaking on a dike slope – principle sketch and control volume.

$$H_b = \gamma d_b \tag{16}$$

with $\gamma = 1.1\xi^{1/6} = 1.1\left(\frac{\tan\alpha}{\sqrt{H/L}}\right)^{1/6}$ (Sunamura, 1980) and $L = \frac{gT^2}{2\pi}$

where γ depends on both the wave steepness and the out dike slope angel α; ξ is the surf similarity parameter which is calculated from the wave height (H) at the dike toe and the deep wave length (L). Typically, $0.5 < \xi < 3.3$ for plunging breakers (Führböter, 1986) and the corresponding γ is in the range 0.98−1.34. In addition, the breaking wave height H_b can be defined as follows (Rattanapitikon and Shibayama, 2000):

$$H_b = K_{KG} H \left(\frac{H}{L}\right)^{-0.2} \tag{17}$$

with $K_{KG} = 10.02(\tan\alpha)^3 - 7.46(\tan\alpha)^2 + 1.32\tan\alpha + 0.55$

Using Eqs. (15)−(17), the proposed semi-empirical formula for the estimation of the slamming pressure becomes:

$$p_y = 2\rho g \frac{1+1.6\gamma}{\gamma} K_{KG} H \left(\frac{2\pi H}{gT^2}\right)^{-0.2} \tag{18}$$

where wave height H is a random variable which can be expressed as a function of the average wave height ($\overline{H}$) and its cumulative probability ($i\%$). So, for convenience only, the H in Eq. (18) also can be expressed in terms of probability distribution function of $\overline{H}$ as:

$$H = H_{i\%} = f\left(i\%, \overline{H}\right) \tag{19}$$

where f is the function of variables $i\%$. Usually, the theoretical distributions of wave heights can be described with a Rayleigh distribution (Battjes and Groenendijk, 2000; Nayak and Panchang, 2015), and the most popular Rayleigh distribution form used in China is expressed as:

$$F(H_i) = P(H \le H_i) = 1 - \exp\left(-\frac{\pi}{4}\left(\frac{H_i}{\overline{H}}\right)^2\right) \tag{20}$$

where P = non exceedance probability; H_i = individual wave height; $H_i/\overline{H}$ = normalized wave height. Using Eq. (20), probability expression function $f(1\%, \overline{H})$ can be expressed as:

$$H = H_{i\%} = f\left(i\%, \overline{H}\right) = \overline{H}\sqrt{\frac{4}{\pi}\ln\frac{1}{1-i\%}} \tag{21}$$

3. Validation of the proposed formula and discussion

Two sources of scale experiments have been collected to validate the proposed slamming pressure formula, i.e., experiments of Führböter (1986) and Stagonas et al. (2012).

3.1. Comparison with the experimental data of Führböter (1986)

The experiments were carried out by Führböter (1986) in two channels for dealing with slamming pressure phenomena due to breaking waves acting on sloping faces of sea dikes: the GWK (Big Wave Channel) in Hannover (length 324 m, width 5 m, maximum water depth 5 m) producing waves up to heights of 2 m and more; a small channel in Braunschweig (width 2 m, maximum water depth 1 m) producing waves up to heights of 40 cm. In both channels, a slope of 1:4 was investigated. In order to obtain the spatial and temporal distributions of the maximum impact forces over the slope of the dike due to plunging breakers, 1-m-element with 21 pressure cells with a sampling frequency up to 2000 Hz was installed along the axis of the slope.

The comparison of measured results with empirical formulae mentioned above is presented in Table 1. It can be seen that: (1) The maximum wave pressures on the dike slope were a little larger than those given by the formula of Ikeno and Tanaka (2003), and the analysis result was in a good agreement with the laboratory data of Kato et al. (2006); (2) Compared with the experimental data, the maximum pressure $p_{99\%}$ in most cases was smaller. The maximum pressure $p_{99\%}$ looks more reliable than $p_{90\%,}$ therefore, the maximum pressure $p_{99\%}$ can be considered as the highest measured maximum impact pressure in practice. Stanczak (2009) and Führböter (1986) seem to have the same view; (3) Interestingly, the proposed formula gives similar results compared to the two formulae by Stanczak (2009), Führböter and Sparboom (1988), suggesting that the proposed formula can be used to predict the slamming pressures on sloping sea dikes.

3.2. Comparison with the experimental data of Stagonas et al. (2012)

A collaboration developed between the University of Southampton, UK and Forschungszentrum Küste (FZK), Hannover had look in more detail at the distribution of pressures induced by waves breaking on the face of a sea dike. For this, 2D large-scale experiments with regular waves breaking on a 1:3 sea dike were conducted by Stagonas et al. (2012) in a large wave flume (length 307 m, width 5 m, water depth 7 m), but a tactile pressure sensor at a sampling frequency of 680 HZ was used to map the impact pressures instead of traditional pressure transducers. But a low sampling frequency may not allow to capture pressure peaks (Stagonas et al., 2012). Wave heights ranging from 0.6 m to 1.0 m and periods between 3 s and 6 s were considered.

The comparison of measured results with empirical formulae mentioned above is presented in Table 2. It can be seen that: (1) These formulae give larger predictions for the slamming pressures compared with the experimental data of Stagonas et al. (2012); (2) The proposed formula give similar results compared to the maximum pressure $p_{99\%}$ by Stanczak formula (2009), but smaller than the maximum pressure $p_{99\%}$ by Führböter and Sparboom formula (1988); (3) The result shows the calculated values by proposed formula are approximately 1.5 times those measured. The prediction is unsatisfactory, principally for two reasons. First, experimental data reported by Stagonas et al. (2012) was measured with low

Table 1
Comparison of measured results (Führböter, 1986) with empirical formulae.

H (m)	T (sec)	ξ	Slamming pressure (KPa)						
			Measured	Ikeno and Tanaka (2003)	Stanczak (2009)		Führböter and Sparboom (1988)		Eq. (18)
					$p_{90\%}$	$p_{99\%}$	$p_{90\%}$	$p_{99\%}$	
0.09	1.3	1.4	4	4	4	5	4	4	5
0.13	1.43	1.2	5	5	5	7	5	6	7
0.16	1.3	1.0	7	6	6	7	6	8	8
0.2	1.51	1.1	8	8	7	9	8	10	10
0.45	2.38	1.1	26	18	17	22	18	22	22
0.76	3.56	1.3	37	30	31	39	30	37	40
0.92	3.37	1.1	36	36	35	44	36	45	46
1.3	4.6	1.3	58	51	53	67	51	64	68

Table 2
Comparison of measured results (Stagonas et al., 2012) with empirical formulae.

H (m)	T (sec)	ξ	Slamming pressure (KPa)						
			Measured	Ikeno and Tanaka (2003)	Führböter and Sparboom (1988)		Stanczak (2009)		Eq. (18)
					$p_{90\%}$	$p_{99\%}$	$p_{90\%}$	$p_{99\%}$	
0.6	3	1.6	18−32	24	31	39	24	30	29
0.6	4	2.1		24	31	39	26	33	32
0.6	5	2.7		24	31	39	27	34	34
0.6	6	3.2		24	31	39	28	35	36
0.7	4	2.0		27	37	46	30	38	36
0.7	5	2.5		27	37	46	32	40	39
0.8	3	1.4		31	42	52	30	37	36
0.8	4	1.9		31	42	52	34	42	40
0.8	5	2.3		31	42	52	36	45	43
0.9	3	1.3		35	47	59	32	41	40
1.0	4	1.7		39	52	65	41	51	48
1.0	5	2.1		39	52	65	44	55	52
1.1	3	1.2		43	57	72	36	46	47

sampling frequency (680 Hz). Second, the proposed formula including other empirical formulae mentioned above neglects air entrainment influence.

4. Discussion

As already stated by Führböter (1986), the air content has an important influence on the slamming pressure, and low air contents give short and high slamming pressures and high air contents give longer and weaker ones. Also, from the analysis of Lin et al. (2012), the entrapped air in breaking waves would lead the "sub-atmosphere pressure" phenomenon to decrease the pressure loading. Unfortunately, the water−air mixture mechanism is complex and the proposed formula including other empirical formulae mentioned above cannot give the corresponding influence. This may lead to underestimate or overestimate of slamming pressure prediction.

There is no clear trend between wave characteristics and the localized pressures that they generate. Indeed, these loads are complex. Despite numerous research works carried out in this field, breaking wave impact loads have not been fully understood. In addition to that, most researches were performed through experiments in the laboratory with serious constraints due to scaling laws, flume dimensions, etc. Field experiment data are necessary to be used for re-examining relevant empirical formulae. So, it is difficult to find out the

Table 3
Comparison of empirical formulae under some wave conditions.

H (m)	T (sec)	ξ	Slamming pressure (KPa)			
			Eq. (18)	Stanczak (2009) $p_{99\%}$	Führböter and Sparboom (1988) $p_{99\%}$	Ikeno and Tanaka (2003)
0.3	1	0.57	12	4	15	12
0.6	1.3	0.52	23	2	29	24
0.6	1	0.40	21	−21	29	24
1.2	2	0.57	48	15	59	47
2.0	3.2	0.7	85	59	98	78

most reliable slamming pressure calculation formula that predicts well for a wide range of wave breaker conditions only through experiment in the laboratory.

It seems that the slamming pressure by the proposed formula is similarly estimated with the $p_{99\%}$ proposed by Stanczak (2009), and actually the two equations have similar form. But, it is found that predictions by Stanczak formula (2009) may be unreasonable when the surf similarity ξ is less than or equal to 0.7 (see Table 3). So, Stanczak formula (2009) is more seriously affected by parameter ξ than other formulae.

5. Conclusions

The results of our research are summarized as follows:

- A semi-empirical formula has been developed to predict the plunging breaker slamming pressures on sloping sea dikes. The main features of the formula are as follows: (1) It takes into account the influence of the wave steepness and dike slope angel on the slamming pressure. (2) It is based on impulse—momentum relation. (3) Assuming wave heights follow Rayleigh distribution, it can converted into a probabilistic expression form for convenience only.
- To verify the validity of the proposed formula, the computational results were compared with the results of two sources of scale experiments. The slamming pressures calculated using the proposed formula were in reasonable agreement with the experimental results.
- Compared to those formulae by Ikeno and Tanaka (2003), Stanczak (2009), Führböter and Sparboom (1988) which had been calibrated from laboratory experiments, the proposed formula can give similar results in most of the wave conditions, suggesting that the proposed formula can be used to predict the slamming pressures on sloping sea dikes.
- Field experiments will result in better understanding of the actual wave force that the structure will experience. Hence the slamming pressures on a sloping sea dike need to be investigated in more detail through field investigations to compare the measured results with the existing empirical equations. This is not discussed in this paper.
- Further research and analysis is still required to explore the accuracy improvement issues in predicting wave slamming pressures.

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