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Experimental Measurements of Wave Overtopping at Seawalls †

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Abstract: There are some 40 cities and more than 50% of the total population living along the coastline of Viet Nam. In line with the rapid urbanization, the natural coast has been gradually concreted thus resulting in more complex and negative impacts of human interventions on the coastal zone. Beside traditional structures as dike and revetment, seawalls have been constructed with various types of cross-sections to protect many towns and tourism areas. However, intensive wave overtopping would possibly threaten the stability of infrastructures and the safety of traffic and residents behind in rough weather conditions such as tropical low pressure, typhoons or monsoons, especially under impacts of climate change. Therefore, the study aims to ascertain quantitatively overtopping phenomenon at seawalls by conducting experiments in a wave flume. We tested four pairs of seawall models with different shapes (curved, steep, straight and stepped), which were positioned on the top of a steep base (1: 1.5). Each pair consists of one model with and another one without bullnose. Test scenarios consists of a normal water level and a higher one taking into account the sea level rise. The obtained data shows that bullnoses help to undermine wave overtopping discharge, and more considerably in case of lower freeboards. In other words, the seawalls with bullnose perform more properly when sea level rise takes place. Besides, bullnoses also help eliminating reflection in front of the structure, thus resulting in less strict requirement of toe protection. To some extent, the findings are expected to partly set-up the base to reduce the scale of coastal protection structures.

Keywords: bullnose; overtopping; reflection; seawall; wave flume

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1. Introduction

There are more than 400 cities and towns stretching over the 3200-km-long coastline of Viet Nam, and 130 more are predicted by the year of 2025 [1]. In line with the rapid urbanization, the natural coast has been gradually concreted thus resulting in more complex and negative impacts of human interventions on the coastal zone. A typical design may consists of a steep revetment and a wave wall/ crown-wall [2] on the top as depicted in Figure 1. This configuration is similar to the structural geometry representing some 700 km of sea dikes in Quang Ninh, Hai Phong, Thai Binh, Nam Dinh and Ninh Binh provinces [3]. In general, the design practice relies very much on experience with dikes and revetments which have been long applied for ages in the north and the central areas, respectively.

Regarding specific conditions of sea dikes in the north of Viet Nam, Tuan et al. [4,5] performed a large number of experiments to verify and improve the formulae of overtopping which were previously introduced in TAW 2002 and later in EurOtop 2007. The tests were designed to explore the effect of the crown-wall height. Using both physical model and numerical model, Thin [3] investigated the influence of low and small crown-walls on overtopping rate. His work also provides insights into the merit of the promenade (space in front of the wall) through an examination of wave-structure interaction. Later, Dung [6] conducted experimental measurements to establish an empirical formulation presenting the effect of bullnose regarding its shape. In these works, the crown-walls usually measures a limited height varying between 0.8 ~ 1.2 m as an official criterion of dike design.

Figure 1. Examples of seawalls protecting coastal towns in Viet nam.

Remarkably, seawalls have been recognized as a reliable measure to protect many towns and tourism hotspots. To heighten the crest, concrete blocks are also placed on existing sea dikes or revetments. Notably, a seawall block is considerably higher than a crown-wall described above. However, intensive wave overtopping would possibly threaten the stability of infrastructures and the safety of traffic and residents behind in rough weather conditions such as tropical low pressure, typhoons or monsoons, especially under impacts of climate change. To reduce more wave overtopping, the design would often consist of a seaward overhang in forms of recurve, parapet, return wall, and bullnose [7–9].

Therefore, this study aims to investigate the interaction between wave and seawall with bullnose standing on a steep base with due attention on wave overtopping. To this end, measurements were carried out with four different shapes of the seawall model in a wave flume. Test scenarios consists of a normal water level and a higher one taking into account the sea level rise.

2. Methods

2.1. Different Shapes of the Seawall Block

The cross-section of any structure plays a vital role in the wave-structure interaction including reflection, running up (on a slope), overtopping and also splashing up. Therefore, we investigated the performance of different seaward faces being curved, steep, straight and stepped (Figure 3). Having the curved shape, T2 model has bullnose while T9 one does not. Similarly, three other pairs are T4 and T5; T10 and T8; and T1 and T3. The curved walls (T2 and T9) are similar to what proposed by Berkely-Thorn and Roberts [10,11]. The straight one T10 is recureve on vertical wall of T8, which probably seems very popular amongst coastal protection structures [8,9,12]. The stepped models (T1 and T3) are inspired by concrete wall at Burnham-on-Sea, UK [e.g., 13].

The seawall models are all made of mica plastic. The first three pairs (T9 and T2; T5 and T4; T8 and T10) are 15 cm high while the stepped ones (T3 and T1) are 20 cm high. Notably, the bullnoses are relatively large with regard to the height of the entire wall. However, all bullnoses are designed to be relatively identical in geometrical shapes as well as dimensions.

2.2. The Wave Flume and Measurement Devices

The model structures and wave parameters are selected according to a length scale of 1/15, a scale ratio [14] of 15. A foreland made of fine sand is shaped with an inclination of 1/100. The seawall is positioned on the top of a steep base ($\cot\alpha = 1.5$). Figure 2 sketches the experiment configuration and the arrangement of measurement devices. Briefly, the flume measures 45 m long (effective), 1.0 m wide and 1.2 m high. The wave maker is equipped with an advanced automated system of Active Reflection Compensation (ARC) and may generate irregular waves with height of up to 30 cm and a peak period of 3.0 s.

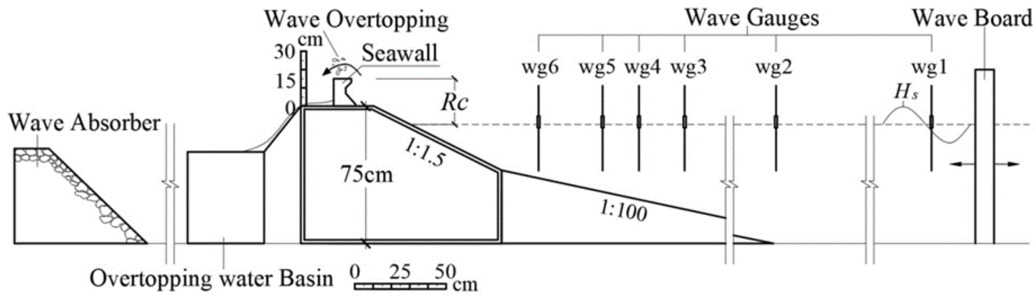

Figure 2. Experimental setup in the wave flume including a wave board, a foreland, a base, a sea wall, a overtopping water tank and a wave absorber (not to scale).

We used capacitance-type gauges to record wave signals at sampling frequency of up to 100 Hz. Four gauges including wg3, wg4, wg5 and wg6 were used to separate reflected waves and thus determine incident waves at the front of the structures [15]. The distances between these gauges are carefully selected so that singularities in the wave separation can be properly avoided. A tank was placed right behind the wall to collect all water produced by overtopping wave and splashing up. A pumping system was installed to keep transferring the water to a bucket for measuring the volume. In short, the experiments were designed to measure two groups of parameters including wave characteristics and overtopping volumes.

2.3. Test Scenarios

We conducted a series of experiments under different wave conditions with standard JONSWAP spectrum. In which, the wave heights were 0.15, 0.16 and 0.17 m while the wave period were 1.5, 1.6 and 1.9 s (Table 1). The flume was filled up 0.6 and 0.65 m representing a normal condition and the sea level rise, respectively. Every test consists of at least 500 waves in order to reproduce the entire spectra and to generate wave overtopping with stable discharges.

Table 1. Test scenarios for all seawall models to be tested.

d [m]	H_{m0} [m]	T_P [s]	T2, T9 curved	T4, T5 steep	T10, T8 straight	T1, T3 stepped
0.60	0.15	1.9	x	x	x	x
0.60	0.16	1.5	x	x		x
0.65	0.16	1.9	x	x	x	x
0.65	0.17	1.6	x	x	x	x

3. Results and Discussion

3.1. Measured Data

We directly measured the total wave overtopping volume V [m³] and the test duration t [second]. As the wave flume is 1 m wide, the averaged unit overtopping discharge q [m³/s per m] is therefore simply derived from these two parameters:

$$q = \frac{V}{t}, \tag{1}$$

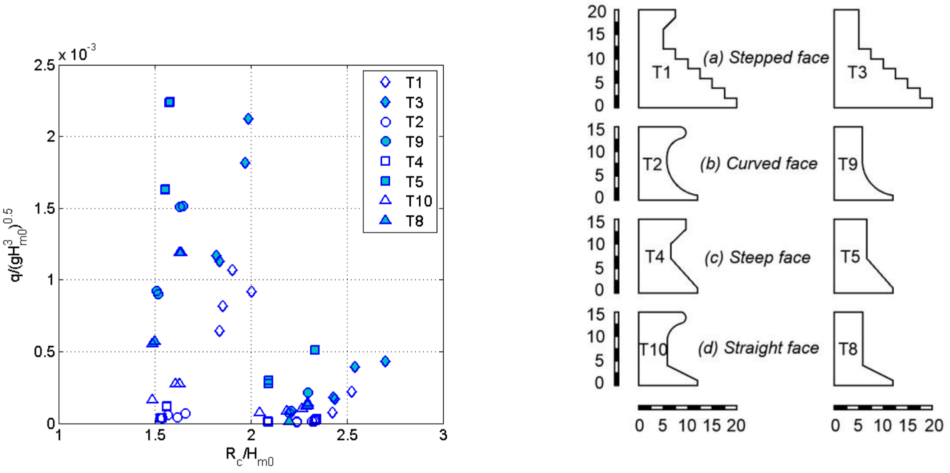

Figure 3. Relative cress freeboard vs. dimensionless overtopping discharge.

From the measured values, we plot the dimensionless crest freeboard R_c/H_{m0} against dimensionless discharge $q/\sqrt{gH_{m0}^3}$ for all tests in Figure 3. Indeed, models with bullnose usually produce less overtopped water rather than those have no bullnose. In general, steep face models (T5 and T4) would produce the largest overtopping discharge while straight ones (T8 and T10) generate the smallest rate. The steep wall without bullnose (T5) is probably comparable to one with steps on the seaward face (T3) when both $q/\sqrt{gH_{m0}^3}$ may reach values of some 2 x 10^{-3} m^3/s per m. In the meanwhile, the amount of water overtopping T4 model is significantly less than T1 model, these two models both have bullnose. It is worth to note that T4 and T5 models are 15 cm high, i.e., 5 cm lower than T10 and T8 ones.

Interestingly, bullnose shows the most significant effect on steep models when $q/\sqrt{gH_{m0}^3}$ drops from (0.27 ~ 2.24) $\times 10^{-3}$ for T5 to (0.01 ~ 0.12) $\times 10^{-3}$ for T4. And for rather high freeboard (R_c/H_{m0}~2), there would be hardly any water overtopping either the curved seawall T2 or the steep one T4. Despite of having bullnose or not, stepped models allow relatively comparable rates of overtopping (0.17 ~ 2.13) $\times 10^{-3}$ for T3 and (0.08 ~ 1.07) $\times 10^{-3}$ for T1.

3.2. Reduction Effect due to the Bullnose

Inspired by existing theories, a reduction factor is computed to quantitatively estimate the effect of bullnose as

$$k_{bn} = \frac{q_{bn}}{q_{nobn}}, \tag{2}$$

in which, q_{bn} and q_{nobn} are overtopping rates on seawall models with and without bullnose, respectively. The smaller the factor the greater amount of discharge which is decreased due to the bullnose. Table 2 shows that the obtained values of k_{bn} cover comparable ranges between curved seawalls (0.039 ~ 0.156) and steep ones (0.023 ~ 0.057); between straight models (0.236 ~ 0.944) and stepped walls (0.428 ~ 0.714). Under wave breaking conditions, recurve/ parapet of high seawalls shows significant effect with a reduction factor smaller than 0.05 [7].

Four model shapes all provide smallest k_{bn} with a water depth of 0.65 m in the wave flume. For curved, steep and straight models, the reduction factor gets maximum value with 0.6-m-deep water. It would be said that bullnoses possibly cause more profound effect with higher water level in the wave flume, i.e., the sea level rise is taken into account. However, this is opposite of what was observed in another series of experiments with the same wall blocks but placed on a steep base of 1/1.5 and followed by a foreland of 1/50 [16]. In other words, a foreland of 1/100 (gentler) may cause more overtopping than one of 1/50 (steeper) regarding the same water level in the wave flume. For comparison, De Bondt measured 4 different nearshore profiles showing that wave overtopping increases with decreasing steepness of the profile [17].

Table 2. Comparison of k_{bn} among different seaward faces. Each k_{bn} is given with corresponding test name, e.g., d60H16T15 means water depth = 0.6 m, wave height = 0.16 m and period = 1.5 s.

k_{bn}	**T2, T9 curved**	**T4, T5 steep**	**T10, T8 straight**	**T1, T3 stepped**
Max	0.156 ~ d60H16T15ii	0.057 ~ d60H15T19ii	0.944 ~ d60H15T19i	0.714 ~ d65H17T16i
Min	0.039 ~ d65H16T19i	0.023 ~ d65H17T16i, ii	0.236 ~ d65H16T19ii	0.428 ~ d65H16T19i
Average	0.073	0.042	0.493	0.555

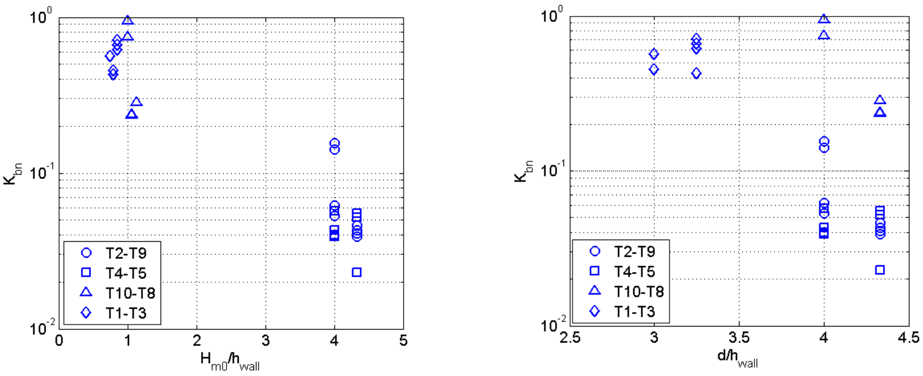

Figure 4. Influence of wave height H_{m0} (left) and water depth d (right) on k_{bn} factor (in log scale).

Figure 4 indicates that the influence of bullnose becomes more effective with higher incoming wave for curved (T2 and T9), steep (T4 and T5) and straight seawalls (T10 and T8), i.e., higher waves lead to smaller k_{bn}. Interestingly, a similar pattern is found when k_{bn} becomes smaller with increasing water depth in the flume for the above shapes. However, bullnose looks resistant against any variation of hydraulic condition when k_{bn} of the stepped models (T1 and T3) remains more or less stable regarding H_{m0} and d.

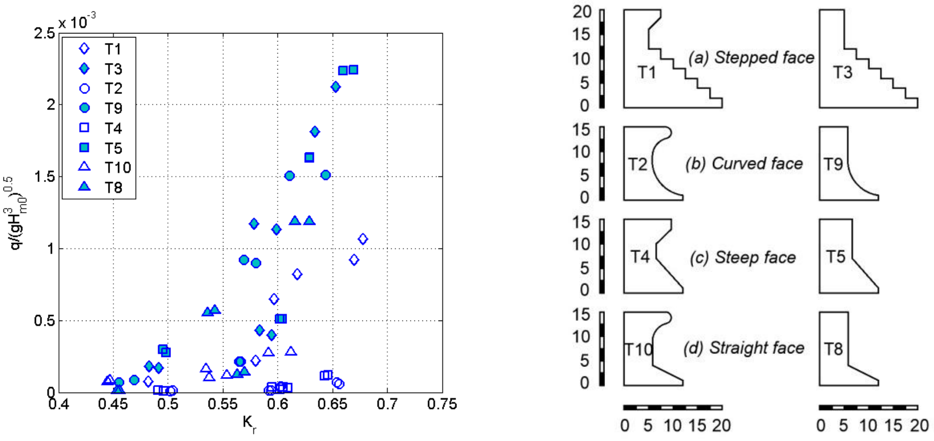

Figure 5. Wave reflection coefficient vs. dimensionless overtopping discharge.

3.3. Wave Reflection Versus Overtopping

Figure 5 plots the reflection coefficient K_r against the dimensionless overtopping discharge $q/\sqrt{gH_{m0}^3}$ for all models to be tested. To some extent, overtopping rate is proportional to the reflection coefficient [18]. For example, Zanuttigh and van der Meer claim that large roughness and permeability induce less overtopping and reflection compared to smooth slope [19]. Remarkably, overtopping discharge shows a rapid increasing as K_r exceeds some 0.55. However, bullnose considerably undermines the effective magnitude of K_r exerting on q as all hollow symbols are locating lower than the solid ones. Consequently, this poses the question as to what extent of reflection coefficient will significantly alter the overtopping discharge at a seawall with bullnose.

4. Conclusions

The paper has presented a series of experiments of wave overtopping at seawalls with regard to sea level rise. We tested four pairs of seawall models with different shapes (curved, steep, straight and stepped); and each pair consists of one model with and another one without bullnose. The obtained data shows that bullnoses help to undermine wave overtopping discharge, and more considerably in case of lower freeboards. In other words, the seawalls with bullnose perform more properly when sea level rise takes place. Respecting the construction aspect, seawall with bullnose may probably optimize the crest level in accordance with lower structure height. On the other hand, the measurements indicate that bullnoses help to eliminate reflected waves. Therefore, toe protection would possibly be thinner and lighter in front of a seawall with bullnose. To some extent, the findings are expected to partly set-up the base to reduce the scale of coastal protection structures under impact of climate change and sea level rise.

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