

CHAPTER 74

NUMERICALLY MODELING PERSONNEL DANGER ON A PROMENADE BREAKWATER DUE TO OVERTOPPING WAVES

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ABSTRACT

Prototype experiments were carried out to quantify when personnel on top of a promenade breakwater will lose their balance due to overtopping waves. The danger of being carried out into the sea was also investigated using model experiments. Based on our results, we developed an empirical formula for calculating the wave height at which personnel danger occurs.

1. INTRODUCTION

Public access to breakwater areas is usually prohibited in Japan due to safety reasons, yet many people nevertheless enter these areas to enjoy the comfortable sea environment. The Japanese Ministry of Transport (MOT) has recently developed a new type of breakwater, named the "Promenade Breakwater," which serves a dual purpose of protecting a harbor from storm waves while also providing the public with amenity areas. **Figure 1** shows a photograph of a promenade breakwater constructed in Wakayama Port.

Because Japanese breakwaters are typically the low-crown type, wave overtopping sometimes occurs, and therefore, it is essential for the design of a promenade breakwater to consider maintaining personnel safety. Based on this important concern, the Port and Harbour Research Institute (PHRI) initiated research to investigate the types of danger a person may be subjected to while on a top of a breakwater.¹⁾²⁾

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Figure 1 Promenade breakwater constructed in Wakayama port

2. PERSONNEL DANGER WHILE ON A BREAKWATER

Personnel danger on a breakwater is closely related to the wave conditions around it. **Figure 2** shows four successive stages of danger that a person can be subjected to while on a breakwater. Here, we classify personnel danger into the following four stages:

- 1st stage: A splash occurs over the breakwater.
- 2nd stage: An overtopping wave occurs.
- 3rd stage: A person is knocked over by the overtopping wave.
- Final stage: A person is carried into the sea by overtopping flow.

When a wave splashes over a breakwater (1st stage), a person may feel scared although no substantial danger exists. The danger, however, is substantial at the 2nd stage, with the 3rd and final stages being extremely dangerous since a serious accident may inevitably happen.

Using experimental results, empirical models were developed to quantify the four stages of personnel danger. **Figure 3** shows a basic flow chart of how the models were employed in the calculations. Wave conditions in the 1st and 2nd stages can be calculated by the overtopping wave model (OWM), which is explained in detail in **Ref. 3**. The "loss of balance model" and "carry model" were developed to quantify the 3rd and final stages, respectively. The present study discusses the danger of each stage, being focused on the 3rd and final stages, and quantitatively describes these conditions using the wave height and wave crest height included in the models.

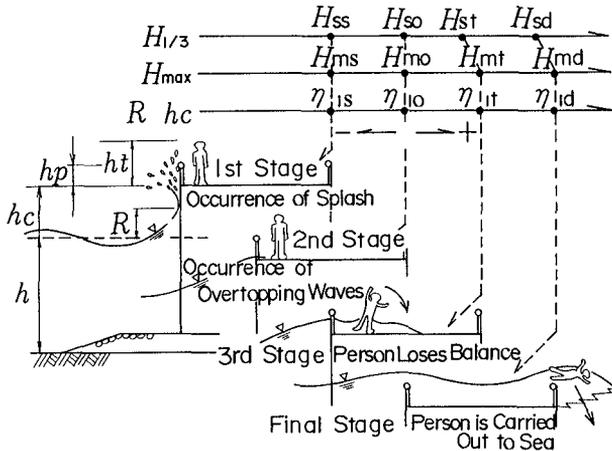


Figure 2 Four successive stages of personnel danger while on a breakwater

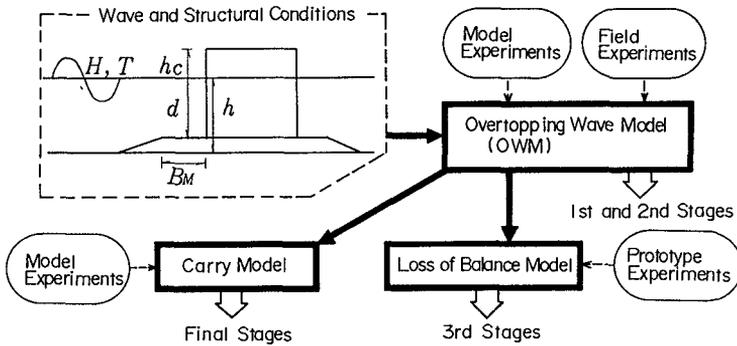


Figure 3 Numerical models of personnel danger while on a breakwater

3. PERSONNEL LOSS OF BALANCE IN OVERTOPPING FLOW

3.1 Prototype Experiments

A series of prototype experiments were conducted in a large current basin (50-m-long, 20-m-wide) to investigate the stability of a person under various flow conditions, i.e., we measured the current force on a person and observed personnel loss of balance.

Component load cells were used to measure the forces acting on three human bodies subjected to steady flow. **Table 1** summarizes the physique of each person (sample A-C). The angle of the person's body against the current, θ , was varied (0, 45 and

Table 1 Physiques of personnel participating in the experiment

	Sample A	Sample B	Sample C
Height (cm)	183	164	174
Weight (kg)	73	65	64
Deviation from standard weight (%)	-2.3	12.8	-3.9
Length of inside leg (cm)	88	73	80
Waist (cm)	78	80	76

90°), as was the width between feet, L_f (0, 25 and 50 cm). Three different types of clothes were used.

Loss of the balance under various flows was observed with a high-speed video camera (200 frames/s). Two pairs of shoes with different type soles were used, having a coefficient of friction μ_s of 0.71 and 0.37. L_f was 25 cm and θ was 0, 90, and 180°.

Figure 4 shows the current force acting on a person's body in steady flow, where the x-axis indicates the current velocity and the y-axis indicates the force of current acting on the body. This force is proportional to the flow velocity squared, and can be expressed as a drag force:

$$F = \frac{w_0}{2g} C_D \cdot A \cdot U^2 \quad (1)$$

The coefficient of the drag force, C_D , is dependent on several parameters, i.e., θ , L_f , and water depth, and can be expressed as

$$C_D = 1.1(1 - L_f/ht) \quad : \theta = 0^\circ$$

$$1.1(1 + L_f/ht) \quad : \theta = 45^\circ, 90^\circ, \quad (2)$$

where A is the projected area of the body against overtopping flow, U the current velocity during wave overtopping, w_0 the specific weight of sea water, and g the gravitational acceleration. Note that when $L_f \neq 0$, $C_D = 1.1$.

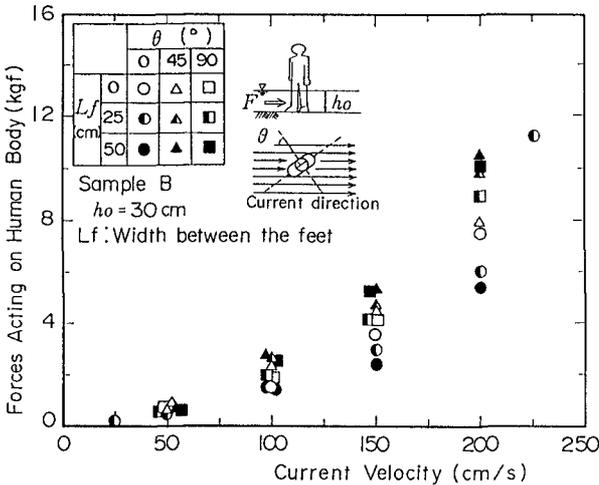


Figure 4 Current forces acting on a person's body

3.2 Loss of Balance Model

Figure 5 represents the loss of balance model which considers the two main types: "tumbling" and "slipping". In the tumbling type, a person is knocked over by the overtopping flow in the downstream direction. This type occurs when the moment produced by the current forces around the feet is greater than the moment produced by the person's weight, being expressed by

$$F \cdot h_G \geq W_0 \cdot l_G, \tag{3}$$

where h_G is the vertical distance from the floor to the point where the resultant force acts, W_0 is the weight of a human body in overtopping flow, and l_G is the horizontal distance between the center of the gravity and the fulcrum of the moment.

In the slipping type, a person is knocked over in the upstream direction, which occurs when the current force is greater than the friction force between the shoes and ground. This type of loss of balance is represented using

$$F \geq \mu_s \cdot W_0, \tag{4}$$

where μ_s is the coefficient of friction between the shoes and the ground.

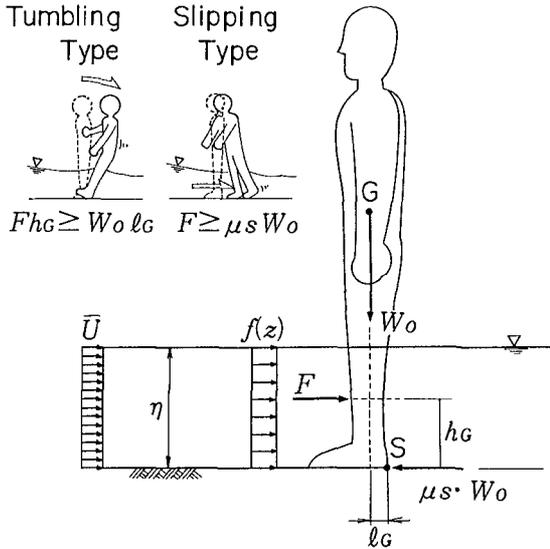


Figure 5 Effect of overtopping flow on the static balance of a person

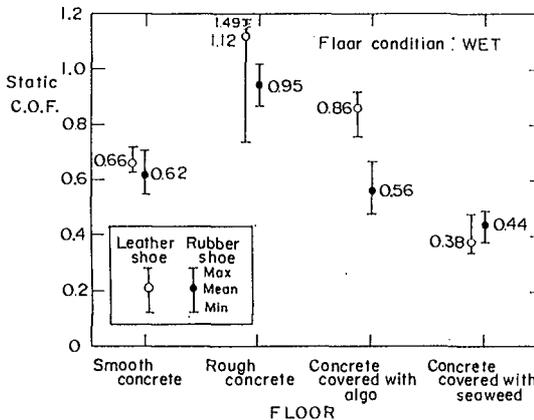


Figure 6 Coefficient of friction between shoe and wet concrete

Figure 6 shows measured field values of μ_s between the shoes (leather and rubber soles) and various types of wet concrete (smooth concrete, rough concrete, concrete covered with alga, and concrete covered with seaweed), where μ_s for the rough concrete is larger than that for smooth concrete. If the floor is covered with alga or seaweed, μ_s naturally decreases. In the loss of balance model, we used a μ_s value of 0.4 for covered concrete and 0.6 otherwise.

3.3 Loss of Balance Observation

Figure 7 shows analogue data of water depth, current velocity, and force acting on the human body, where the current velocity increases after the current generator starts. When the current velocity is 165 cm/s and the force acting on the human body is 14 kgf, a person is knocked over (slipping type loss of balance) as shown in **Fig. 8** (the flow direction is from left to right and the person faces upstream). μ_s between the shoes and ground was about 0.3.

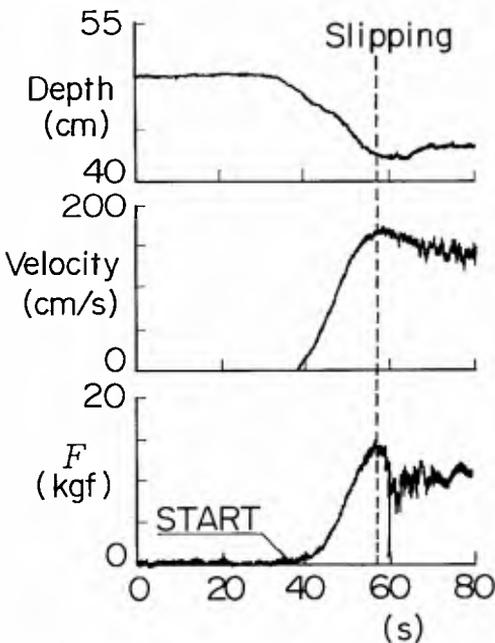


Figure 7 Measured analogue data during loss of balance experiment

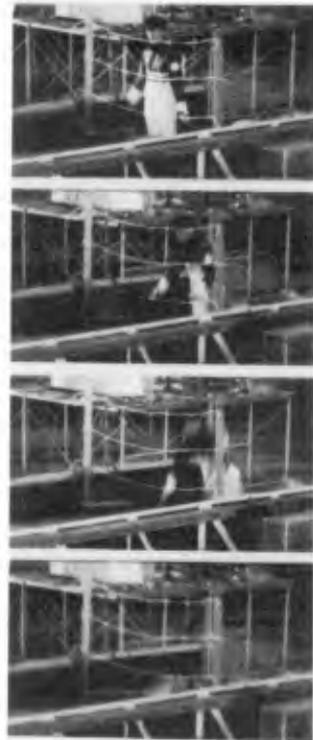


Figure 8 Loss of balance by slipping

Figure 9 shows experimental results of a person's stability under various flow conditions. The x-axis is the water depth where the person is standing, while the y-axis is the current velocity there. The solid line indicates the calculated stable limit as determined by the slipping type loss of balance model. The good agreement between the calculated and experimental results is clearly apparent.

Figure 10 shows the critical water depth on a caisson at the seaward edge, η_{11} , when a person is knocked over. η_{11} is calculated by the loss of balance model in which we assumed that $\mu_s = 0.4$, the person is standing at the most dangerous location facing the seaward side ($\theta = 0^\circ$), and the person's legs are spread to 22% of their height. Note that η_{11} tends to increase as the person's height increases or as the body shape becomes more slender. If a person is 152 cm in height and has a standard body shape, $\eta_{11} = 50$ cm. In this condition, the tumbling type loss of balance occurs at the seaward edge of a caisson where the maximum current velocity is 0.9 m/s.

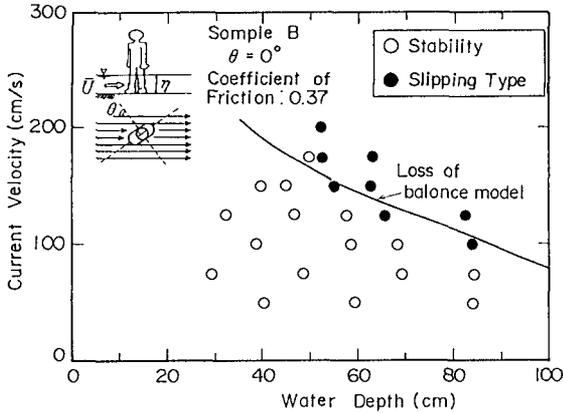


Figure 9 Verification of the loss of balance model

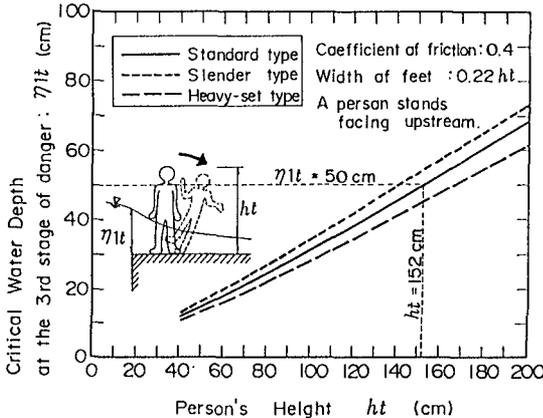


Figure 10 The relation between a person's height and wave crest elevation when loss of balance occurs

4. CARRIED INTO THE SEA BY OVERTOPPING WAVES

4.1 Outline of Model Experiments

A series of model experiments were conducted in a wave channel to investigate the danger of a person being carried into the sea by overtopping waves. Experiments involve measuring overtopping flow with handrails present and observation of human body movement.

We measured the motion of overtopping waves using a wave gauge, current meter, and high-speed video camera. Handrails were installed at the seaward and landward edge of a caisson.

Figure 11 shows model handrails having four opening ratios $\epsilon = 0, 0.24, 0.44, \text{ or } 0.61$.

The motion of a human body model in overtopping flow was also observed by a high-speed video camera under various wave conditions with different shaped handrails. The human body model has a cylindrical shape with a diameter of 2 cm and height of 7.6 cm. At a model scale of 1/20, the corresponding height is 152 cm. It is made from wood whose specific gravity is 0.8.

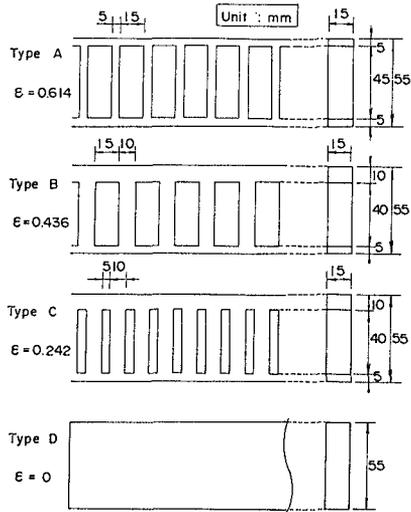


Figure 11 Diagram of model handrails

4.2 Handrail Effects on Overtopping Flow Motion

Figure 12 shows the seaward handrail's effect on water depth on a caisson during wave overtopping. The x-axis is the maximum water depth on a caisson at the seaward edge, η_1 , and the y-axis is that 40 cm from the seaward edge, $\eta(x = 40)$. When no handrail is installed, $\eta(x = 40)$ is about 40% of η_1 . If a handrail is installed at the seaward edge, the water depth behind it decreases in comparison to that if no handrail is present. Note that the water depth decreases as the opening ratio of the handrail decreases. The effect of a handrail can be quantitatively estimated as

$$\eta(x) = 0.4 \{ \eta_1 - hp(1 - \epsilon_1)^2 \}, \tag{4}$$

where hp is the height of the handrail and ϵ_1 is the opening ratio of the seaward handrail.

Figure 13 shows the distribution of the maximum flow velocity on a caisson near the landward handrail with an opening ratio of 0.61. The length of a vector indicates the flow velocity value, while the solid line indicates the maximum water depth on the caisson. Since this handrail has a high ϵ_2 value, the flow near it is not even disturbed. However, if the handrail's ϵ_2 is small, the water depth near it will significantly increase. This effect can be formulated as

$$\eta_2 = \min \{ \eta_1, 0.4\eta_1 + (1 - \epsilon_2)hp \}, \tag{5}$$

where ϵ_2 is the opening ratio of the landward handrail and η_2 is the maximum water depth at the landward edge.

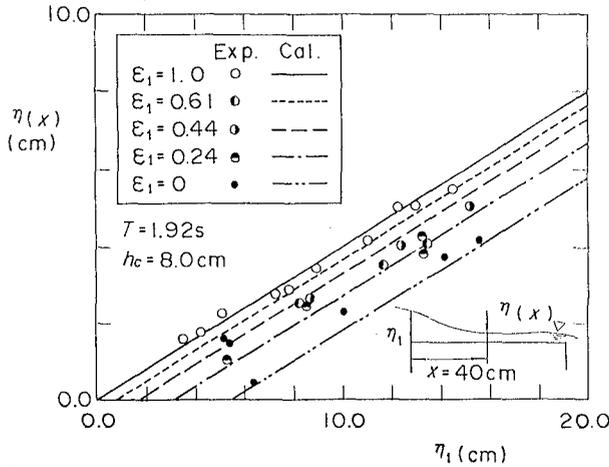


Figure 12 Maximum water depth behind the seaward handrail

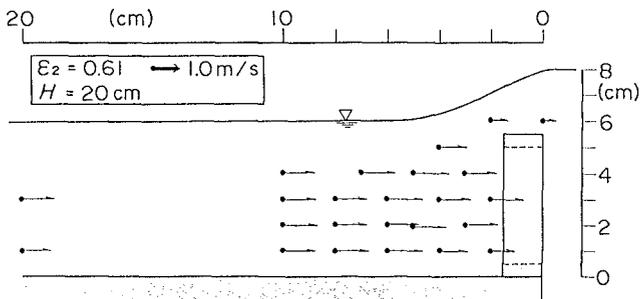


Figure 13 Distribution of current velocity near the landward handrail

4.3 Body Motion in Overtopping Flow

Figure 14 shows wave-induced movement of the human body model when it is placed near the landward handrail. Each diagram depicts the effect of ϵ_2 on model movement. When $\epsilon = 0$, the higher handrail is considered to be an impermeable wall. Note that as ϵ_2 decreases, the model is lifted up; thereby indicating a strong relation exists between movement and the water depth near the handrail, i.e., the maximum water depth at the landward handrail strongly influences whether or not a person will be carried into the sea. The critical water depth at which the model was carried over the handrail into the sea was found to be about 17% of its height. An expression representing this danger is

$$\eta_{2cr} = 0.17ht + hp, \tag{6}$$

where η_{2cr} is the critical water depth at the caisson's landward edge which will carry a person into the sea, and ht is a person's height.

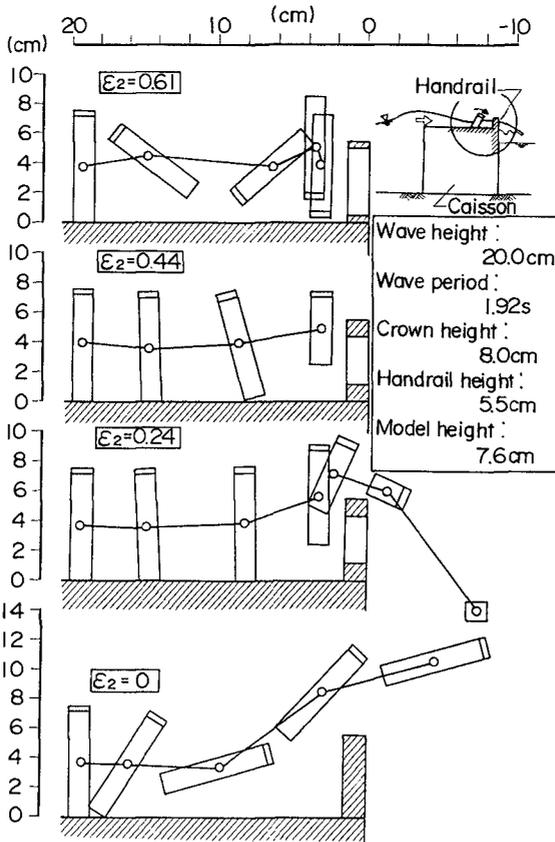


Figure 14 Diagram of human body movements in overtopping flow at various ϵ_2 values

4.4 Carry Model

The carry model can estimate the effect of the seaward and landward handrails on the maximum water depth using Eqs. (4) and (5), respectively, whereas Eq. (6) enables calculating the maximum water depth at the caisson's seaward edge which will carry a person into the sea.

Figure 15 shows the critical water depth (contour lines) at the caisson's seaward edge as determined by the carry model. The x- and y-axis respectively indicate the opening ratio of the seaward and landward handrail. It is assumed that a person is 152-cm tall and the height of the handrails is 110 cm. As shown, if no handrails are installed, the critical water level is only 0.7 m. However, if both handrails have an opening ratio of 0.7, this increases the critical water depth to 2.1 m. These results verify that handrails effectively prevent a person from being carried into the sea.

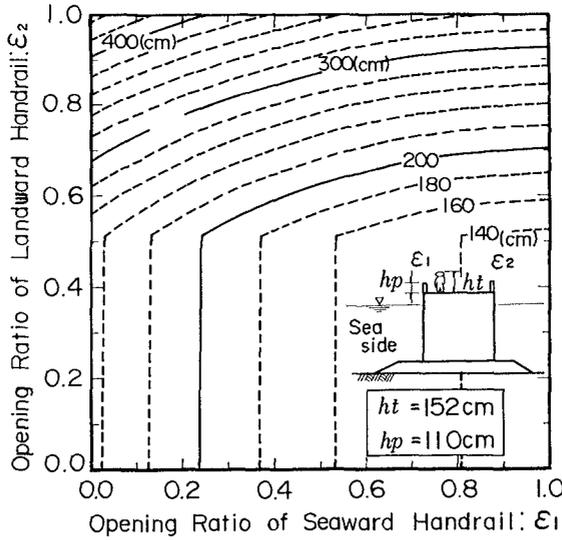


Figure 15 The critical water depth on the caissons seaward edge which carries into the sea

5. WAVE HEIGHT DURING EACH DANGER STAGE

5.1 Dangerous Wave Height Formula

As shown next, the wave height at each successive stage of danger can be formulated by the OWM.

5.1.1 Critical wave height of splash: H_{ms}

$$H_{ms} = \frac{-1 + \sqrt{1 + 2.8\alpha_1 hc/hm}}{2\alpha_1} \times hm \tag{7}$$

$$\begin{aligned} hm &= d && : B_M/L \geq 0.16 \\ d + (h - d) \frac{0.16 - B_M/L}{0.05} &&& : 0.11 < B_M/L \leq 0.16 \\ h &&& : 0.11 < B_M/L \end{aligned} \tag{8}$$

where hc is the breakwater's crown height, and α_1 is a coefficient representing the breakwater superstructure, being 1.0 for a vertical breakwater and 0.5 for a slit-caisson breakwater or a composite breakwater with wave-dissipating blocks. Also, d is the water depth above the mound foundation, h the water depth above the sea bottom, B_M the width of the mound shoulder, and L the wave length at the depth of the breakwater.

5.1.2 Critical wave height at overtopping: H_{mo}

$$H_{mo} = \frac{-1 + \sqrt{1 + 4\alpha_1 (hc + hp^*)/hm}}{2\alpha_1} \times hm \tag{9}$$

$$\begin{aligned} hp^* &= 0 && : \varepsilon_1 \neq 0 \\ hp &&& : \varepsilon_1 = 0 \end{aligned} \tag{10}$$

where hp is the handrail height and ε_1 is the opening ratio of the seaward handrail

5.1.3 Critical wave height for being knocked over: Hmt

$$Hmt = \frac{2(hc^* + \eta_{1t})}{1 + \sqrt{1 + 4\alpha_1 hc^*/hm}} \tag{11}$$

$$\begin{aligned} hc^* &= hc && : \varepsilon_1 \geq 0.4 \\ &hc + hp && : \varepsilon_1 < 0.4 \end{aligned} \tag{12}$$

where η_{1t} is the maximum water depth at the caisson's seaward edge when a person is knocked over. In Eq. (11), η_{1t} is assumed as 0.5 (m), which is the critical value for a 152 cm tall person (average 12 years old person in Japan).

5.1.4 Critical wave height for being carried into the sea: Hmd

$$Hmd = \frac{2(hc + \eta_{1d})}{1 + \sqrt{1 + 4\alpha_1 hc^*/hm}} \tag{13}$$

where η_{1d} is the maximum water depth at the caisson's seaward edge when a person is carried into the sea (Table 2, Figure 16).

Table 2 η_{1d} against the types of handrail ($hp = 1.1$ m) for 152 cm tall person (unit : m)

Seaward handrail	Fence type	Wall type	Chain type or nothing
Landward handrail			
Fence type	2.1	3.1	2
Wall type	1.5	2.5	1.4
Chain type or nothing	0.8	1.3	0.7

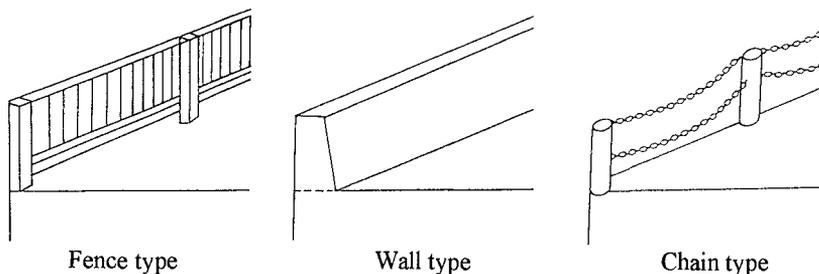


Figure 16 Handrail types

5.2 Example Calculation

Using the following conditions, an example will be shown calculation that determines the critical wave for causing danger at each danger stage;

$$hc = 2 \text{ m}, hp = 1.1 \text{ m}, d = 8 \text{ m}, h = 10 \text{ m}, B_M = 5 \text{ m}, \epsilon_1 = \epsilon_2 = 0.7, T = 6 \text{ s}.$$

Under these conditions, a splash occurs over the breakwater at a maximum wave height $H_{max} \geq 1.2 \text{ m}$ (*Hms*), while overtopping wave occur at $H_{max} = 1.7 \text{ m}$ (*Hmo*). A person on the breakwater is knocked over at $H_{max} \geq 2.1 \text{ m}$ (*Hmt*), and is carried over the handrail into the sea at $H_{max} \geq 3.5 \text{ m}$ (*Hmd*). If no handrails are installed, however, the final stage requires an H_{max} value of only 2.3 m.

A significant wave height for occurring dangers without breaking condition are assumed to be the H_{max} value divided by 1.8 for splash and overtopping danger (*Hss* and *Hso*), while the H_{max} value divided by 2.0 for 3rd and final stages of danger (*Hst* and *Hsd*), i.e., $Hss = 0.7 \text{ m}$, $Hso = 0.9 \text{ m}$, $Hst = 1.1 \text{ m}$, and $Hsd = 1.8 \text{ m}$ under the same condition.

6. EFFECTS OF OVERTOPPING FLOW RATE ON PERSONNEL DANGER

Figure 17 shows the relationship between the significant wave height and the overtopping flow rate under the same conditions used in the example calculation. The overtopping flow rate is calculated using the OWM⁽³⁾, which can evaluate this flow rate and the maximum overtopping flow rate for a regular wave. The overtopping flow rate for irregular waves is calculated based on the assumption that the Rayleigh distribution of wave heights holds. We assume the wave number is 1700, in which the maximum wave height is just two times the significant wave height.

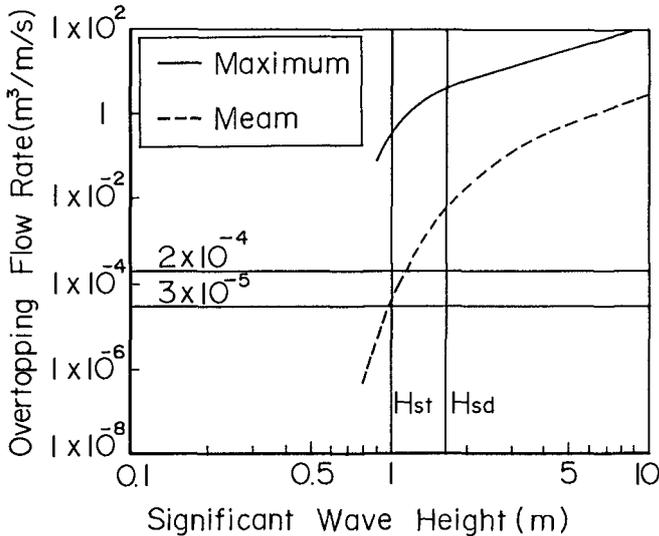


Figure 17 Overtopping flow rate when a person faces the several danger

Under these conditions and those used in the example calculations, the mean overtopping flow rate that knocks over a person is $4 \times 10^{-5} \text{ m}^3/\text{m/s}$, while at $6 \times 10^{-3} \text{ m}^3/\text{m/s}$ the person is carried into the sea.

Fukuda et al. (1974) found that the wave overtopping flow rate to provide a probability of 50 and 90% personnel safety on a seawall is 2×10^{-4} and $3 \times 10^{-5} \text{ m}^3/\text{m/s}$, respectively. Note that our overtopping flow rate for being knocked over falls within these probabilities of safety.

7. CONCLUDING REMARKS

The types of overtopping wave-induced personnel dangers that can occur while standing on a breakwater were experimentally investigated. Our main conclusions are:

- 1) Based on prototype experiments, we developed a loss of balance model to calculate the critical water depth at a breakwater's seaward edge. If a person is 152-cm-tall and has standard body physique, the critical water depth is 0.5 m which causes a person to their balance.
- 2) The proposed carry model can calculate the critical water depth at the breakwater's seaward edge which will carry a person into the sea. This depth is dependent on the opening ratios of handrails installed at the breakwater's seaward and landward edge. If fence-type handrails having a 0.7 opening ratio are installed at the both edges, the critical water depth is 2.1 m for a 152-cm-tall person.
- 3) When no handrails are present, the calculated critical water depth which carries a person into the sea is only 0.7 m for a 152-cm-tall person, thus handrails are demonstrated to be a very effective measure for preventing a person from being carried into the sea by overtopping waves.
- 4) The proposed breakwater formula for evaluating the wave height at which personnel dangers will occur during successive stages of wave overtopping should be employed in the design of promenade breakwaters.

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