CHAPTER 17

Quantity of Spray Transported by Strong Wind over Breaking Waves

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Abstract

The quantity of spray transported by strong wind has been measured experimentally when the wind blows over waves propagating on a sloping bed. The leeward variation of spray concentration is much smaller than that in the vertical direction because of the quasi uniform supply of spray from the water surface. In the theoretical development, therefore, the balance has been analyzed between the upward flux of the concentration by turbulent diffusion and the downward flux due to the spray precipitation. Three characteristic quantities introduced in the analysis have been obtained by superposing the experimental data on the theoretical solutions. They are related to the wave and wind parameters to predict quantitatively the spray concentration supplied from sea to shore.

1. Introduction

Japan is well known as a country which many typhoons pass through every year. Two big typhoons hit successively the western

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Fig. 1. Schematic diagram of experimental set-up.

part of Japan on September 1991. They gave extensive severe damages along the coastal region, such as the stoppage of electric current over more than four days and poor harvest of crops. A report of the investigation showed that a large quantity of spray of sea water distributed over a wide area and it caused these disasters. To predict the magnitude of the salt damage, it is necessary to evaluate how much the quantity of spray is transported from sea to shore. Some studies (e. g., Toba, 1959; Toba & Tanaka, 1967; Hama & Takagi, 1970) have been already made on the generation and transport of sea-salt particles. However, many fundamental problems have been left unsolved.

In this study, the quantity of spray which is transported when strong wind blows over breaking waves has been measured experimentally, and the discussion has been made about vertical and leeward profiles of the spray concentration.

2. Experimental arrangements

Experiments were carried out by using a wave tank. It was equipped with an inhalation-typed wind tunnel. Its schematic diagram is shown in figure 1. The tank was 32 m long, 0.60 m wide and 1.30 m high. It was covered with a semicircular cylindrical ceiling whose As a model beach, a sloping flat bed of 1/30-grade radius was 0.37 m. The mean depth of water was 0.52 was fixed at one side of the tank. m at the horizontal bed section. Spilling breakers were formed by making two-dimensional regular waves propagate on the sloping bed. The wave parameters are given in table 1, where T is the wave period and H₀, L₀ and C₀ are the wave height, wavelength and wave velocity in deep water, respectively.

The wind was taken into the tank by opening a part of the ceiling. Water spray entrained into the air was captured by arranging vertically ten or twelve cylindrical containers filled with cotton. Their diameter and length were 3.0 m and 5.0 cm, respectively. The vertical interval

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Run	T(s)	H ₀ (cm)	L ₀ (cm)	C ₀ (m/s)	U _m (m/s)	H_0/L_0	U _m /C ₀	γ
1		1			12.0		6.15	
2	1.25	11.6	243.7	1.95	16.8	0.048	8.63	0.2
3					19.4		9.95	
4					12.0		7.69	
5	1.00	10.9	156.0	1.56	16.9	0.070	10.8	0.4
6					17.5		11.2	
7					12.1		7.76	
8	1.00	14.0	156.0	1.56	16.9	0.090	10.8	0.6
9					19.1		12.2	

Table 1. Experimental parameters.

between the containers was 5.0 cm. As shown in figure 1, the test section was 15.0 m long. The positions from p1 to p16 were datataking stations. Their leeward interval was 1.0 m except for Run 6, in which it was 1.2 m. At each station, wave height, wave set-up and spray quantity were measured. The concentration of spray in the air C (g/cm³) was obtained by dividing the mass of spray transported per square centimeter and second by the cross-sectionally averaged wind velocity U. The wind velocities U_m given in table 1 are ones obtained by averaging U in the leeward direction. The values of non-dimensional parameters H_0/L_0 , U_m/C_0 and γ are also given in table 1. The parameter γ will be mentioned in §3.2 and 3.3.

In the following discussion, the horizontal coordinate axis x is taken in the leeward direction from the center of the wind intake. The vertical axis z is taken upwards from wave crest at each data-taking station.

3. Results and discussion

3.1 Transport of spray by wind

Photo 1 shows the generation of spray from a spilling breaker under strong wind. It was taken at x = 10 m in Run 6. A large amount of spray is occurring from the breaking crest.

Photos 2(a) and (b) show vertical profiles of spray size obtained by using droplet sampling paper, t being the time for which the paper had been exposed to spray. The paper is made of filter paper, and a solution of aniline blue dye in benzine is applied to it. From these profiles, it is seen that the spray size decreases remarkably in the



Photo 1. Generation of spray from spilling breaker under strong wind.





t= 6.3 s, t= 28 s (b) x=15.0 m.





Fig. 2. Vertical profiles of spray concentration.

vertical direction but the vertical profiles do not change so rapidly in the leeward direction.

Figures 2 (a) to (c) show some examples of vertical profiles of spray concentration C. The values of C increase with the increase of x. The rate of increase in the leeward direction is one or two orders of magnitude over ten and several meters. On the other hand, the change in the vertical direction is much larger than that in the leeward direction. The values of C decrease vertically upwards to three or four orders of magnitude over about 40 cm. It means that the supply of spray from the water surface is almost uniform in the leeward direction.

3.2 Theoretical development

The following assumptions have been made in the theoretical development.

• The field is steady and two-dimensional.

• The leeward variation is much smaller than the vertical one.

• Vertical mean velocity is nearly equal to zero.

Under these assumptions, the governing equation for the spray concentration becomes

$$\frac{\partial}{\partial z} \left(D \frac{\partial C}{\partial z} \right) + \frac{\partial}{\partial z} \left(w_0 C \right) = 0, \tag{1}$$

where D is the coefficient of turbulent diffusion and w_0 the settling velocity of spray. Boundary conditions are given by

$$C = C_*(x, 0) \qquad \text{at } z = 0$$

$$C \to 0 \qquad \text{as } z \to \infty$$
(2)

Let us introduce the dimensionless quantities defined by

and

$$f(\tilde{z}) = C/C_{*}(x, 0), \quad g(\tilde{z}) = D/w_0 l_{*}(x, 0) \text{ and } \tilde{z} = z/l_{*}(x, 0),$$
 (3)

where $l_{*}(x, 0)$ is a characteristic length scale defined as a value of D/w₀ at z = 0. Substituting equation (3) into equation (1), we obtain

$$df/d\tilde{z} + g^{-1}f = 0 \tag{4}$$

Considering that the diffusion coefficient increases generally with z, w_0 decreases oppositely because of the decrease of the spray size with z and g(0)=1, we can assume the form of g as follows.



Fig. 3. Vertical profiles of theoretical solutions for various values of y.

$$g = (1 + \tilde{z})^{\gamma} . \qquad (\gamma > 0)$$
(5)

Substituting equation (5) into equation (4) and using f(0) = 1, we obtain the solution

$$f(\widetilde{z}) = \exp\left[\frac{1}{1-\gamma}\left\{1-\left(1+\widetilde{z}\right)^{1-\gamma}\right\}\right].$$
 (6)

Since $f(\infty) \rightarrow 0$, γ must take a value from 0 to 1.

Figure 3 shows the vertical profiles of the theoretical solutions for various values of γ . As γ increases, spray diffuses to higher elevation and the vertical profile C becomes uniform. Therefore, it is the result which can be accepted easily.

3.3 Quantification of spray concentration

To predict quantitatively the spray concentration, the quantities introduced in the theoretical development, C_* , l_* and γ should be related with the wave and wind parameters. For their evaluations, the method



Fig. 4. Degree of agreement between the non-dimensionalized experimental data and theoretical solutions.



Fig. 5. Relation between γ and H₀/L₀.

was used of superposing the experimental data on the theoretical solutions in log-log graph paper, and the theoretical curve fitting best to the experimental data was determined by the method of trial and error. The values of γ determined by this method are given in table 1. Figures 4 (a) to (c) show the degree of agreement between the experimental data and theoretical curves. Though some scattering can be seen in the upper region, the agreement between the both is very good in the lower region. From table 1, it is seen that γ does not depend on U_m/C_0 but H_0/L_0 . In figure 5, the values of γ are plotted against H_0/L_0 . The values of γ increase linearly with the increase of H_0/L_0 .

The leeward variations of C* (x, 0) are given in figures 6 (a) to (c). The values of C* increase gradually with x. After reaching the maximum value C* max, it decrease rapidly. It results from the decrease of the supply of spray due to the wave propagation into a swash zone. C* max is an important quantity to evaluate the maximum quantity of spray transported from sea to shore. In figure 7, the values of C* max/ ρ_0 are plotted against Um/C₀, where ρ_0 is the density of water. They increase exponentially with the wind velocity.

Figures 8 (a) to (c) give the leeward variations of l_* . The values



Fig. 6. Variations of C* in the leeward direction.



Fig. 7. Relation between C* $_{max}/\rho_0$ and Um/C₀.

of l_* are approximately constant in the leeward direction and tend to decrease with the increase of the wave steepness. Here, let us define $\overline{l_*}$ as a value of l_* averaged in the leeward direction. Figure 9 shows the relation between $\overline{l_*}$ /H₀ and H₀/L₀. The values of $\overline{l_*}$ /H₀ decrease linearly with the increase of H₀/L₀ without depending on U_m/C₀.

It should be noted that the relatively small leeward-variations of C_* and l_* guarantee the validity of the second assumption made in §3.2.

4. Conclusions

In the case when strong wind blows over breaking waves, the vertical and leeward profiles of spray concentration are investigated experimentally and theoretically. The leeward variation is much smaller than that in the vertical direction. The non-dimensional vertical profiled is expressed by a exponential function. The three characteristic quantities to determine the spray concentration supplied from sea to shore, i. e., the maximum concentration at the elevation of wave crest C* max, a characteristic length scale of the vertical profiles $\overline{l_*}$ and the non-dimensional parameter determing the vertical profile of the ratio of the diffusion coefficient to the settling velocity Y are related to the wave and wind parameters. The values of C* max increase exponentially with the increase of wind velocity. The values of Y



Fig. 8. Variations of l_* in the leeward direction.



Fig. 9. Relation between $\overline{l_*}$ /H₀ and H₀/L₀.

depend only on the wave steepness and increase with its increase. On the other hand, the ratios of $\overline{l_*}$ to the wave height decrease linearly as the wave steepness increases. The non-dimensional vertical profile of spray concentration and the evaluation of C_{* max}, $\overline{l_*}$ and γ enable us to know how much the spray concentration is supplied from sea to shore. It offers us the boundary condition on the sea side in calculating the spray concentration on land.

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