CHAPTER 110

FAILURE OF RUBBLE MOUND STRUCTURES DUE TO THE STORM DURATION AND THE IRREGULARITY OF OCEAN WAVES

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Abstract

Failure mechanism and destruction processes of rubble mound structures under the irregular wave attack are discussed in considering with the effects of wave grouping, storm duration, and structural conditions using the model test results. In the analysis of the stability, a new irregular force parameter that affect the failure of rubble mound structures is defined by combining wave grouping characteristics, storm duration effects and wave-structure interaction mechanisms. Using the external force parameter, a modified rubble mound design formula is suggested, and its applicability is proved by the results of comparative studies with the conventional results.

1. Introduction

Wave climate, irregularities and uncertainty of ocean waves, and wave-structure interactions are the important parameters in the design of rubble mound structures. Remarkable efforts to develop design formulas of rubble mound structures considering irregular ocean waves have been made by Ryu and Sawaragi (1986), van der Meer (1988), and many of other researchers. Sawaragi et al. (1985) and Ryu et al. (1984) developed the design formula introducing the irregularity of ocean waves. Ryu and Sawaragi (1986) improved it considering allowable damage, material and/or block characteristics, spectral shape effects of ocean waves on the stability of rubble mound structures. Van der Meer (1988) proposed similar advanced design formula considering

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the storm duration, allowable damage, and the permeability of rubble mound structures. However, any of the results can't explain sufficiently the destruction mechanism and processes of rubble mound structures by the effects of storm duration and the irregularity of ocean waves including wave-structure interactions.

In the study, define a modified irregular force parameter that can consider the spectral shapes, wave-structure interactions and storm duration effects on the stability. Using the experimental data (Ryu, 1984), the destruction processes will be analyzed with the conception of storm duration effects, and combining the relation between the damage level increase and the irregular force parameter, a new design formula of rubble mound structures will be developed, and the applicability will be discussed by comparing with conventional results.

2. Conventional Design Formulas and Problems

The parameters considered in the conventional design formulas to estimate stable rubble weight (W) for the monochromatic wave can be summarized as:

$$W = f_1(H, \theta, \gamma_w, \gamma_s, f) + f_2(T(L), \beta, D, P, i, h, \gamma_a, h_c) + f_3(\cdots\cdots) \quad (1)$$

where H = wave height

θ = slope angle

γ_w, γ_s = relative weight of sea water and cover material, respectively

f = friction coefficient

$T(L)$ = wave period (length)

β = incident wave angle

D = allowable damage ratio (%)

P = permeability coefficient

i = slope of sea bottom

h = water depth

γ_a = thickness of cover layer

h_c = crest height.

The most design formulas considered only the parameters in the f_1 of Eq. (1), and the effects of parameters in f_2 and f_3 were introduced as a constant to correct the stability. Since the variety of the constant, the design results are varied by the career of designer and selection of design formula, however, the design rubble weight (W) are presented to be proportional to the H^3 (Ryu, 1984).

$$W \geq \alpha H^3 \qquad (2)$$

where α represents the proportional constant.

The variation of the design results will be largely increased, if the irregularity of ocean waves are introduced in the design concept. As shown in Fig. 1, the degree of rubble weight change can be pointed out as an important technical problem to develop a new design conception that minimize the scattering. In the figure, Ryu's (Ryu and Sawragi, 1986) and Meer's (van der Meer, 1988) formulas are to the irregular waves, and others are to the regular waves. It can easily found that the design rubble weights changed to 2 times or more due to the difference of coefficients and formulas.

In the case of irregular waves, following irregularity parameters of ocean waves should be considered additionally in Eq. (1).

$$W = f_{irr.}\,(H_{1/n},\ \xi_{1/n},\ E_{sum}\,j(\,),\ Q_p,\ N,\ D,\ P,\ \theta,\ \phi,\ \gamma_w,\ \gamma_s,\ \cdots\cdots) \qquad (3)$$

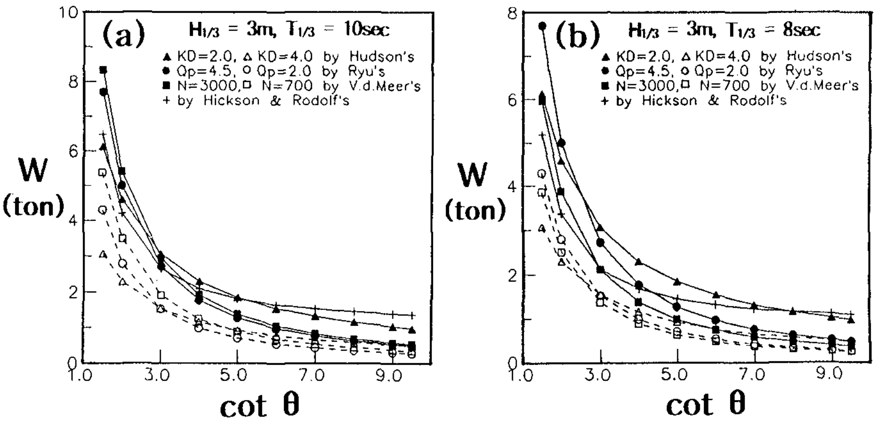


Fig. 1. Design weights of rubble units in relation to the slope angle by various formulas.

where $H_{1/n}$ is the statistic wave heights, $\xi_{1/n}$ the surf similarity parameter using $1/n$ significant waves, Q_p the spectral peakedness parameter (Goda, 1985), N the number of incident waves, ϕ repose angle of cover material. $E_{sum}j(\ )$ denotes the concept of run-sum which is defined as the mean energy level of group formated waves as Eq. (7).

The representative design formula for irregular waves was proposed by parameterization of the effects of wave grouping/spectral shapes, wave periods/wave-structure interactions and the allowable damage level considering equilibrium slope formation as follows (Ryu and Sawaragi, 1986):

$$W_r \geq \left[\frac{\gamma_w (6.15 Q_p + 20.0)}{\gamma_s^{1/3} (D + 30.1)} \frac{\tan\theta}{\tan\phi} \right]^{3/2} H_{1/3}^3 \tag{4a}$$

for the uniform slopes

$$W_r \geq \left[\frac{\gamma_w (5.46 Q_p + 17.73)}{\gamma_s^{1/3} (D + 36.3)} \frac{\tan\theta'}{\tan\phi} \right]^{3/2} H_{1/3}^3 \tag{4b}$$

for the composite slopes

$$Q_p = \frac{2}{m_0^2} \int_0^\infty f\, S^2(f)\, df$$

in which W_r denotes the design rubble weight by Ryu's formula, allowable damage ratio D denotes percentage of eroded volume of cover layer to the total eroded volume until the damage level directly affects the stability of filter layer stones, m_0 the zero-th spectral moment, $S(f)$ the spectral density function, f the frequency.

Another design formula on irregular waves was proposed by van der Meer (1988) considering the permeability and storm duration etc. as follows:

$$W_v \geq \frac{\xi_m^{3/2} \gamma_s H_{1/3}^3}{[\ 6.2 P^{0.18} (D_v/\sqrt{N})^{0.2}]^3 (\frac{\gamma_s}{\gamma_w} - 1)^3} \tag{5a}$$

for $\xi_m < \xi_c$

$$W_v \geq \frac{\gamma_s H_{1/3}^3}{[\ P^{-0.13}(D_v/\sqrt{N})^{0.2}(\cot\theta)^{0.5}\xi_m^P]^{\ 3}(\frac{\gamma_s}{\gamma_w}-1)^3} \tag{5b}$$

$$\text{for } \xi_m > \xi_c$$

where ξ_m is surf similarity parameter using mean wave period, D_v is the damage level defined by van der Meer (1988) that has the relation of $D_v = 0.08D$. Eqs. (5a) and (5b) correspond to plunging and surging breakers, respectively classified with transition value of surf similarity parameter ξ_c given by

$$\xi_c = (6.7\ P^{0.31}\sqrt{\tan\theta})^{\frac{1}{P+0.5}} \tag{6}$$

Though these design formulas are the most advanced, each has not included important parameters in Eq. (3). Ryu's formula (Ryu and Sawaragi, 1986) did not account for the effects of storm duration effect and structural permeability, and van der Meer(1988) neglected the wave grouping characteristics. To overcome before mentioned shortcomings and scatterings, the improved formula is needed to develop. It can be pointed out that such storm duration and wave grouping statistics is not clarified statistically as design parameters to introduce in actual design. However, it can be emphasized that the irregularities should be considered in the experiments on the stability and reliability check for the reasonable design.

3. Analysis of Available Data

3.1 Experimental Features and Analysis

Destruction mechanism and damage processes are investigated used the results of hydraulic model tests in addition to previous works of Ryu (1984), and Ryu and Sawaragi (1986). The tests were carried out with 3 kinds of structural slopes 1:1.5, 1:2.0, 1:3.0 on a uniformly sloping beach of 1/40 with controling the permeability of core layer to correct the scale effects. Irregular waves are generated with various spectral shapes of 200 cases. The destruction processes were visualized simultaneously with incident waves by the 16 *mm* high speed cine camera (50 *frames/sec*) during the experiments.

Destruction mechanism is reanalyzed to investigate the effects of irregular wave parameters and correct the effects of resonance phenomena on the slope by introducing the tolerable destruction concept. And storm duration effect on destruction process is analyzed by measuring the destruction history to the irregular wave trains.

3.2 Analysis of Wave Irregularities as a Design Force Index

Waves used in the experiments were analyzed by wave by wave analysis and spectral analysis methods, and wave grouping parameters that is important to stability of rubble mound structures were evaluated. The wave grouping parameters such as run-length $j(\ )$ and run-sum were defined same as Ryu (1984). The mean run-sum (E_{sum}) is defined as the mean of energy-sum of group formated waves shown in Eq. (7). In the study, the mean run-sum of conditional run of ξ_o^* under the condition of significant wave height, $E_{sum}j(\xi_o^*|H_{1/3})$ is introduced as a grouping parameter that affects to the stability. From the previous work by an author (Ryu and Sawaragi, 1985) on relations among the mean run-sum and Q_p, it can be estimated by the following formula.

$$E_{sum}j(\ ) = \sum_{j=1}^{\infty}\sum_{k=1}^{\infty}\frac{1}{8}\gamma_w H_k^2 \,/\, \sum_{j=1}^{\infty} N_{j(\ )} \tag{7}$$

$$E_{sum}j(\xi_o^*|H_c) = \gamma_w H_c^3 (0.04\, Q_p + 0.13) \quad \text{for } H_c = H_{1/3} \tag{8}$$

$$\xi_o^* = \{1.5 \le \xi_{1/3}^* \le 2.5\} \tag{9}$$

$$\xi_{1/3}^* = \frac{\xi_{1/3}}{\xi_{max}} = \frac{\tan\theta/\sqrt{H/L_o}}{\tan\theta/\sqrt{(H/L_o)_{max}}} \tag{10}$$

where $H_k(k=1,2,3,...)$ is k-th wave of run-length $j(\ )$, $j(\ )$ denotes the run-length j of the run of ( ), N_j is number of wave group with the run-length j. The breaker types could be classified by surf-similarity parameters ξ, and the range of Eq. (9) makes the resonance phenomena on the slope by wave by wave interaction.

Ryu and Sawaragi (1986) defined irregular force parameter [X] including wave grouping and resonance phenomena, and arranged the correlation with destruction ratio $D(\%)$ as follows:

$$[\mathrm{X}] = \left[\frac{E_{sum}\, j(\xi_o^*|H_{1/3})}{\gamma_s\, l_a^2} \frac{\tan\theta}{\tan\phi} \right] \tag{11}$$

$$D(\%) = 153.8[\mathrm{X}] - 30.1 \tag{12}$$

in which l_a is the characteristic length of stone/block. Eq. (12) did not consider the effects of storm duration and permeability of structures.

3.3 Analysis of Destruction Processes

Destruction mechanism and processes of rubble mound structures can be explained with combining the effects of storm duration time, resonance phenomena and wave force parameter [X] shown as Eq. (13). The contribution of the effects to the damage level illustrated schematically in Fig. 2.

$$D(\%) = A N^{0.25} [\mathrm{X}] \tag{13}$$

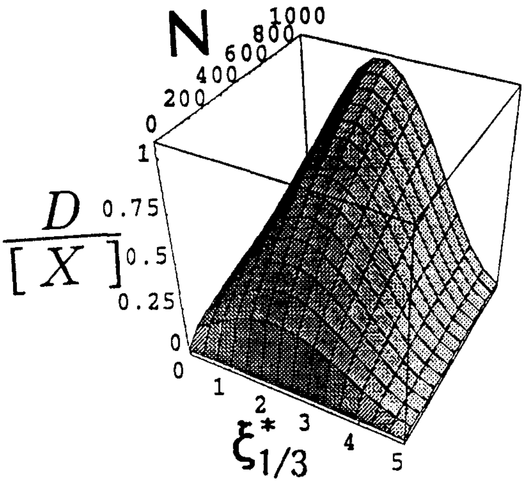


Fig. 2. Schematic definition of weighting function.

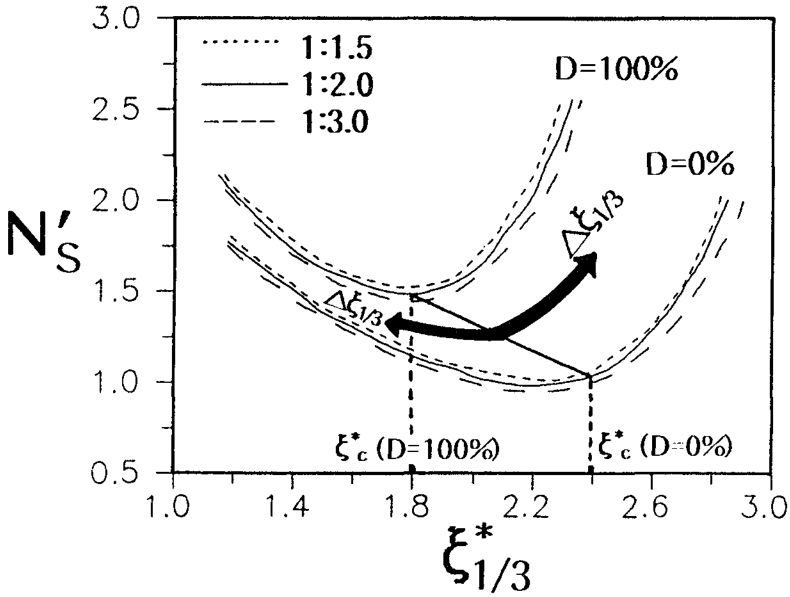


Fig. 3. Variation of modified stability number according to relative surf-similarity number.

Damage of rubble mound structures is strongly related with the waves in the range of $1.5 < \xi^*_{1/3} < 2.5$ where the minimum point of modified stability number (N_S') is appeared as shown in Fig. 3. From Fig. 3 by Ryu and Sawaragi (1986), it can be pointed out that critical surf similarity parameter ξ^*_c with the minimum point of modified stability number decrease with the damage level increase.

$$N_s' = \frac{\gamma_w^{1/3} H_{D(\%)}}{(\gamma_{s/\gamma_w} - 1)\, W^{1/3}} \frac{\tan\theta}{\tan\phi} \tag{14}$$

where $H_{D(\%)}$ is the design wave height for the damage level in percent $D(\%)$. In the case of tolerable destruction ratio $D = 0\%$, minimum point of N_s' located at about 2.3 of relative surf similarity parameter $\xi^*_{1/3}$, in $D = 100\%$, about 1.8. If the critical surf similarity parameter ξ^*_c can be assumed to be linearly changed according to tolerable damage ratio, it is represented as follows:

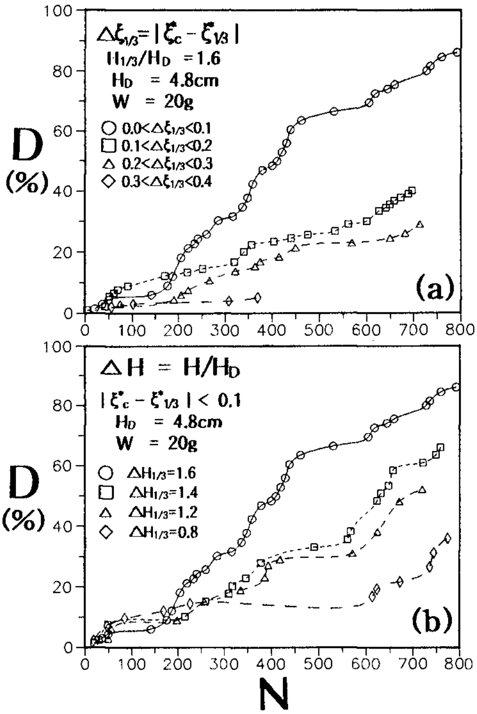


Fig. 4. Storm duration effects on the failure of rubble mound structures with the resonance indexes $\triangle\xi^*_{1/3}$ (a) and $\triangle H_{1/3}$ (b).

$$\xi^*_c = 2.3 - 0.005\,D \tag{15}$$

Dimensionless damage level to irregular force parameter has a peak around critical surf similarity parameter ξ^*_c and decrease with increase of $\triangle\xi^*_{1/3}$ ($= \xi^*_c - \xi^*_{1/3}$) in Fig. 3. This was proved by investigating of the effects of the resonance indexes, $\triangle\xi^*_{1/3}$ and $\triangle H_{1/3}$ to the failure of rubble mound structures as shown in Fig. 4. In the figure, it is clarified that the damage level increase is affected by decrease of $\triangle\xi^*_{1/3}$ and increase of $\triangle H_{1/3}$ with the storm duration time N. Considering the characteristics, a weighting function was introduced as Eq. (16) by trial and error method with storm duration effect.

$$A = C_1 \cos\left(\frac{\xi^*_c - \xi^*_{1/3}}{2}\right) = C_1 \cos\left(\frac{(2.3 - 0.005D) - \xi^*_{1/3}}{2}\right) \tag{16}$$

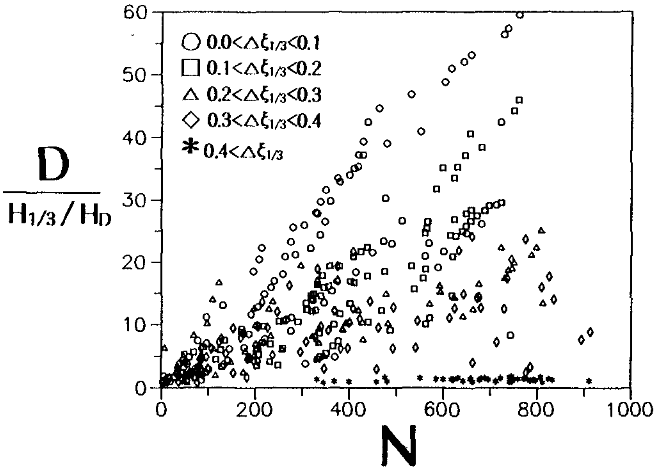


Fig. 5. Damage level increase of rubble mound structures according to the resonance indexes and the storm duration effects.

Combining Fig. 4(a) and (b), the damage level change due to storm duration under the condition of various $\triangle\xi^{*}_{1/3}$ is shown in Fig. 5. It can be said that the severe damage will occur at smaller $\triangle\xi^{*}_{1/3}$. Dimensionless damage level to the force parameter $[X]$ and weight function A was compared versus the storm duration. The result of this analysis presented in Fig. 6. The variance of the results is considerable, however, if one wants to design more reliable structures considering uncertainty of damage processes, the upper limit of the figure will be applied, and the trend of damage increase whose resonance index is close to 0 can be presented as follows:

$$\frac{D}{A[X]} = C_2 N^{0.25} \tag{17}$$

Using the relations, the destruction processes can be summarized and formulated combining constants C_1 and C_2 to C as follows:

$$A N^{0.25} = C \cos\left(\frac{(2.3 - 0.005D) - \xi^{*}_{1/3}}{2}\right) N^{0.25} \tag{18}$$

where C is a constant of 0.194 from the data.

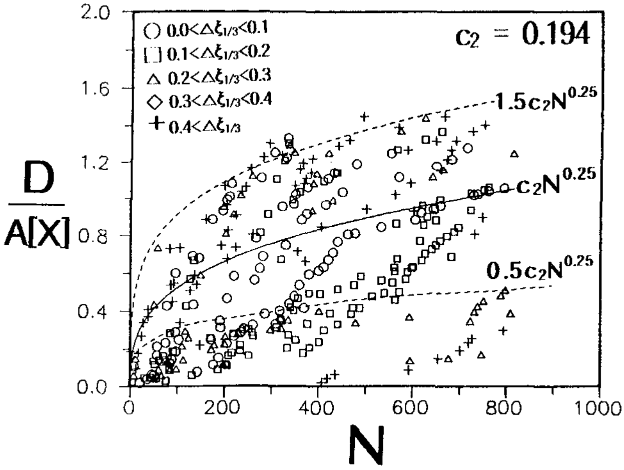
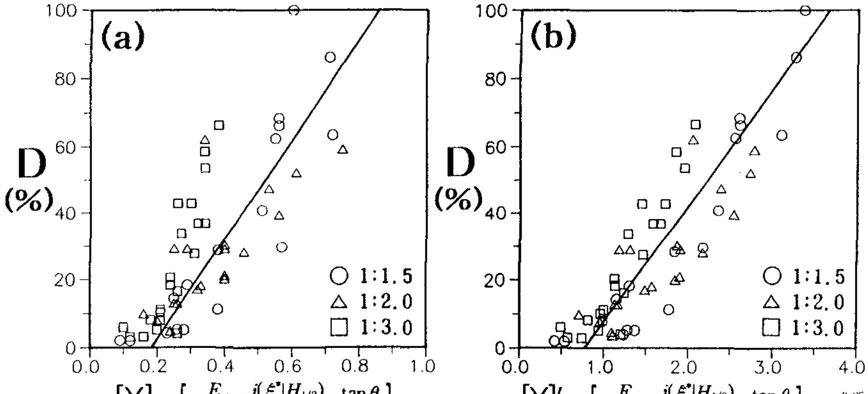


Fig. 6. Variation of damage level according to the storm duration.

4. Development of Design Formula

To develop a design formula considering the effects of irregularity of ocean waves and storm duration time on destruction processes as written in Eq. (18), the relationships between damage level (D) and modified irregular force parameter $[X]'$ were investigated by comparing with previous result used $[X]$. Fig. 7 shows the results,



$$[X] = \left[\frac{E_{sum}\, j(\xi_o^* | H_{1/3})}{\gamma_s\, l_a^2} \frac{\tan\theta}{\tan\phi} \right] \qquad [X]' = \left[\frac{E_{sum}\, j(\xi_o^* | H_{1/3})}{\gamma_s\, l_a^2} \frac{\tan\theta}{\tan\phi} \right] A N^{0.25}$$

Fig. 7. Comparisons between failure characteristics with respect to the previous irregular force parameter (a) and the modified parameter (b).

and it can be clarified that the modified force parameter [X]′ represents very well the damage processes than [X]. The correlation between the damage ratio and the new force parameter can be derived empirically as:

$$D = 29.84\,[X]' - 5.82 \tag{19}$$

$$[X]' = A\,N^{0.25}\,[X] \tag{20}$$

By the relation, the formula to calculate the design weight of a rubble unit can be rearranged to as follow:

$$W_{new} \geq \left[\frac{\gamma_w(1.19\,Q_p+3.88)}{\gamma_s^{1/3}\,(D/A\,N^{0.25}+5.82)} \frac{\tan\theta}{\tan\phi} \right]^{3/2} H_{1/3}^3 \tag{21}$$

Using the new design formula and conventional formulas, the variation of design weight of a rubble unit is compared according to the storm duration under the same conditions of other parameters. Fig. 8 shows a typical example of variation of design weight of rubble unit. The design weight becomes heavier according to the longer storm duration, and the difference between new formula and others are significant by irregular wave conditions and allowable

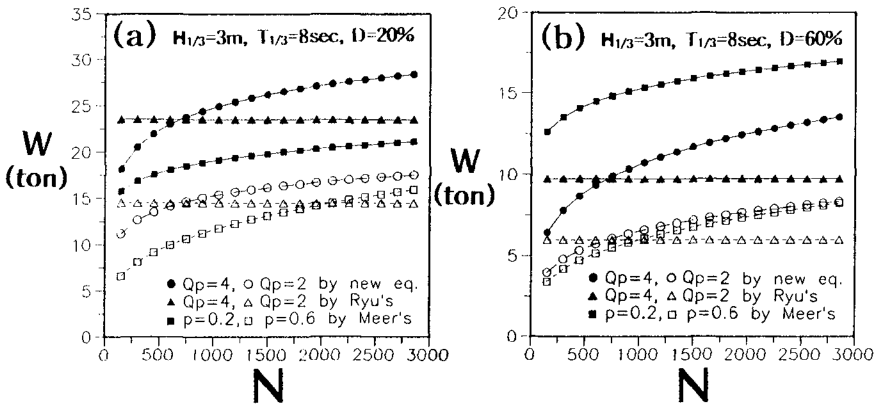


Fig. 8. An example of design weight of rubble unit in relation to storm duration.

damage level(D). This point out the importance of storm duration as well as the force parameter. It is emphasized that the wave grouping effects/spectral shape effects is one of the most important parameter in the new formula while neglected in van der Meer's formula.

Many researchers including authors pointed out the importance of permeability in rubble mound structures, but it is difficult to formulate using effective parameters on the stability. Kaku et al. (1991) developed a design formula using the experiments by van der Meer (1988), which was simplified as function of P and ξ_m, however, it has also problems for sensitivity analysis to the irregularity of waves.

To expand the new formula to the variable permeability, stability analysis parameter Q_s can be defined by combining the experimental results by author(1984) and van der Meer(1988).

$$Q_s = \frac{\xi_m \cot\alpha}{7.3\, C_k^2 P^{0.36}} - 3.32 \qquad (22a)$$

$$\text{for } \xi_m < \xi_c$$

$$Q_s = \frac{P^{0.26}}{0.19\, C_k^2 \xi_m^{2P}} - 3.32 \qquad (22b)$$

$$\text{for } \xi_m > \xi_c$$

where C_k denotes constant as introduced by Kaku et al. (1991). This formula represents the effect of Q_p to the stability in use of the new formula by introducing ξ_m and P of van der Meer's formula Eq. (5).

Stability analysis method could be formulated with regard to the storm duration, wave grouping characteristics, resonance phenomena and permeability, however, the parameters can not easily get in the field data. In future, field measurement to get a design parameter should be designated to satisfy the estimation of the force parameter, and the experiments should be designed to cover the effects. It is needed to consider the effects of crown height and wave-structures-soil interactions in the design.

These methods and data will be contributed to database as design constraints with numerical models on wave-structure interactions in the applications of the optimal design algorithm developed by Ryu et al.(1992).

5. Conclusions

Destruction processes of rubble mound structures are investigated by the hydraulic experiments considering irregularities of ocean waves and storm durations. The main results obtained in the study are:

1) From the analysis of destruction mechanism and its process, the effects of wave grouping and spectral shapes of irregular ocean waves, storm duration and wave-wave interaction on the slopes are emphasized as the important parameters in the analysis of stability of rubble mound structures.

2) The destruction processes are formulated empirically introducing the new irregular force parameter included the storm duration and resonance phenomena in addition to the irregular force parameter. And a modified design formula is proposed by rearranging the relationship between the damage level and the modified force parameter to calculate weight of rubble units.

3) By the comparative study with previous works, it can be emphasized that the new formula represents reasonably the effects of storm duration, wave irregularities, damage increasing processes, and wave-wave interaction on the slope. Applicability of the formula and research needs were discussed to the comprehensive optimal design algorithm of rubble mound structures.

4) The effect of permeability to the stability can be applied by a correct parameter to expand the use of the new formula.

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