CHAPTER 123

Characteristics of Wave Dissipation by Flexible Submerged Breakwater and Utility of The Device

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Abstract

A flexible submerged breakwater called "flexible mound", made of an elastic membrane bag filled with water, has been developed for wave control in shallow water as an advanced alternative to the conventional rigid submerged design. Experimental studies were carried out to compare the characteristics of the wave dissipation by flexible mound with those by rigid models. The appropriate ranges of important parameters affecting the efficiency of the flexible type were identified. Numerical studies were also conducted to investigate the mechanism of wave absorption by the flexible structure. To verify the stability and utility of the flexible mound, additional experimental studies were performed using a prototype model.
A design concept involved in an actual field construction of the flexible breakwater is also presented.

Introduction

With more than 30,000 km of coastlines surrounded by rough seas, detached breakwaters, made of concrete blocks, are commonplace in the coastal scenery of Japan. Although these structures serve the intended purpose of shore protection, their undesirable effects on the scenic value of shorelines have been questioned recently. For development of marine recreational zones, there is a particularly strong demand for invisible yet safe and effective wave control methods. Conventional submerged rigid dikes could partially meet this need if it is made very wide with its height close to the water surface. However, it is often too massive for general

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applications, and breaking waves and fast currents around the structure could be dangerous to swimmers and small boats. In response to this demand, and as an alternative to the rigid submerged design, the authors have devised a submerged flexible breakwater called "flexible mound", made of an elastic membrane bag filled with water. Earlier studies by Tanaka et al. (1987) and Kiyokawa et al.(1987) have shown that characteristics of wave dissipation by the flexible mound are substantially different from those by a rigid model, and that the flexible mound can effectively dissipate waves even when the submergence ratio is greater than 0.4. The authors have also identified some important parameters and their appropriate ranges for optimum performance of the flexible design.

The objective of the present study is to investigate the mechanism of wave absorption by the flexible mound by physical and numerical model analyses. Experimental studies using a prototype model are also carried out to verify stability and utility of the flexible submerged breakwater.

Modeling Approach

The concept of the flexible mound and the definition of parameters used in the present study are shown in Figs.1 and 2, where p_0 is the static internal added pressure; ρ : the fluid density; g : the gravitational acceleration; ρ_m : the membrane density; ε : the membrane thickness; and E : Young modulus of the membrane.

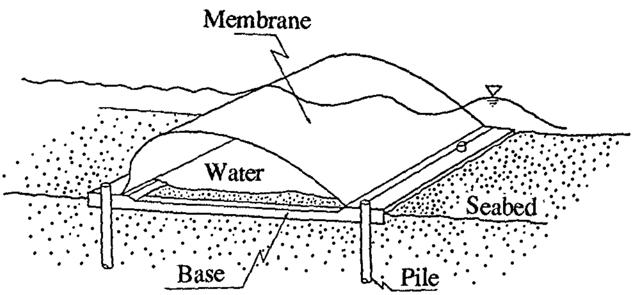

Fig.1 Concept of Flexible Mound (FLM)

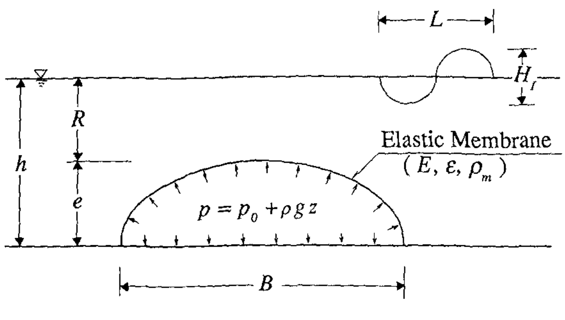

Fig.2 Definition sketch & modeling using lumped-mass method

Since numerical model has been described in detail by Ohyama et al. (1989), only an outline of the numerical analysis is presented here. In this modeling approach, the elastic membrane is discretized into small elements using the lumped-mass method as shown in Fig.3. Forces acting on j-th nodal point are shown in Fig.4; where F_j is the hydrodynamic force caused by the pressure difference between the interior and the exterior of the membrane, f_j and f_{j-1} are the tensions acting on j-th and j-1-th spring , and f_0 is the net weight of the mass in the water. These forces can be represented by using the velocity potentials on the surfaces of the membrane and amplitudes of the membrane motions for all elements. In addition to the assumption inherent in the velocity potential, the motions of the fluid and the membrane are assumed to be sufficiently small, so that the linear theory can be applied. The boundary value problem for the potentials can be transformed into boundary integral equation by applying Green's function and Green's formula. Discretizing the integral equations into finite elements, linear equations for the velocity potentials and the amplitudes of the membrane are obtained.

Wave transmission coefficient, K_T, and reflection coefficient, K_R, are obtained from the potential values on the free surface sufficiently apart from the structure.

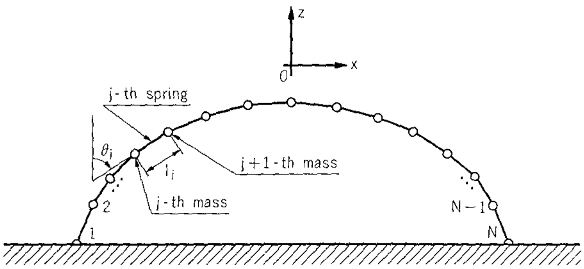

Fig.3 Modeling by the lumped-mass method

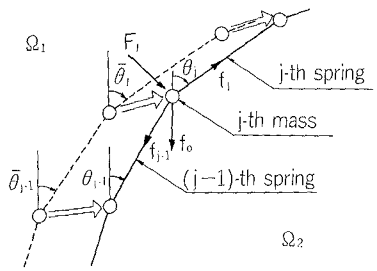

Fig.4 Forces acting on j-th nodal point

Experiments

Physical model experiments were carried out in a wave tank, 40 m long, 0.6 m wide and 1.3 m deep as shown in Fig.5. Two models of the flexible mound were made of reinforced rubber membrane fiber with Young modulus, $E=5800\ N/cm^2$, density, $\rho_m=1.2\ g/cm^3$, and thickness, $\varepsilon=1.5$ mm. The models were then hermetically sealed, filled with water and installed on the bottom of the wave tank. A rigid model was also examined for comparison of mobility effects on wave dissipation. The model configuration and the wave conditions are listed in Tables 1 and 2. During the experiments, it was observed that the stationary component of the internal pressure p_0 shifts steadily upward by Δp_0 as a train of waves traverses over the flexible model. Therefore, $p_0' = p_0 + \Delta p_0$ is the virtual internal pressure during experiments.

A comparison between the experimental and the numerical results for the frequency dependence of the transmission and the reflection coefficients, K_T and K_R, is shown in Fig.6, in which B is the base width of the model, and L is the incident wave length. Some discrepancies between the numerical and the experimental results are attributable to the fact that the energy loss by the structure's motion in the experiments was not taken into account in the numerical analysis. Nonetheless, this numerical model can qualitatively evaluate governing parameters and their effects on wave dissipation by the flexible mound.

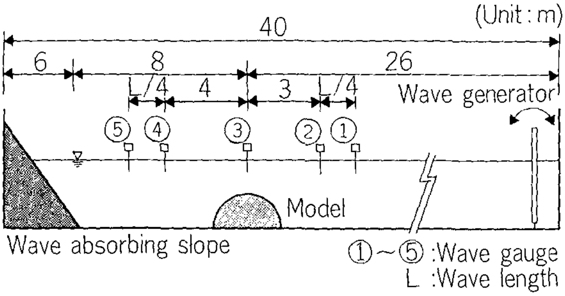

Fig.5 Wave tank layout

Table 1 Model cases

Model type	Width B (cm)	Height e (cm)	Case	Internal pressure p_0 (Pa)	Crown depth R (cm)	B/h	R/h	$p_0/\rho gh$
Flexible A	160	40	A - 1	657	27	2.34	0.4	0.10
			A - 2	329	27	2.34	0.4	0.05
Flexible B	80	19	B - 1	172	16	2.29	0.46	0.05
Rigid C	160	36	C - 1		9	3.56	0.20	

Table 2 Wave conditions

No.	Wave depth h (cm)	Wave height H_I (cm)	Wave periods T (sec)	Length ratio B/L	Note
1 - 1	45	4.5	1.01 ~ 2.65	0.3 ~ 1.05	for B = 1.6 m
1 - 2	45	11.3	1.01 ~ 2.65	0.3 ~ 1.05	
2 - 1	67	4.0	0.93 ~ 3.26	0.2 ~ 1.2	
2 - 2	67	8.0	0.93 ~ 3.26	0.2 ~ 1.0	
3 - 1	35	22 ~ 35	1.01 ~ 4.37	0.1 ~ 0.55	for B = 0.8 m

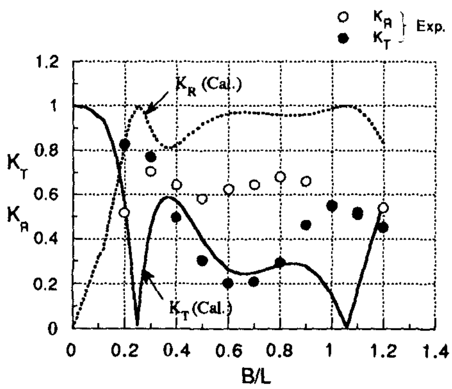

Fig.6 Comparison between numerical and experimental results for wave transmission and reflection characteristics (Case A - 1 : R/h = 0.4, B/h = 2.34, $p_0/\rho gh$ = 0.1)

Characteristics of wave dissipation

According to the customary dimensional reasonings, K_T and K_R may be expressed by the following dimensionless parameters:

$$K_T, K_R = f\left(B/L, B/h, R/h, R/H_I, p_0/\rho gh, E/\rho_m gh, \rho_m/\rho, \varepsilon/h\right) \qquad (1)$$

A preliminary study (Ohyama et al., 1989) has indicated that, among the eight dimensionless parameters in the group, three parameters, $E/\rho_m gB$, ρ_m/ρ, and ε/h are insignificant in the practical range of application. The rest of the parameters, dimensionless frequency, B/L; width to water depth, B/h; submergence ratio, R/h; relative internal added pressure, $p_0/\rho gh$; and crown depth to incident wave height, R/H_I, have influence on the performance of wave control by the flexible structure.

A previous study (Tanaka et al., 1990) has shown that the appropriate ranges of the parameters, B/h, R/h and $p_0/\rho gh$, in order to obtain good performance for a wide range of B/L are B/h : 1.5 ~ 3.0, R/h : 0.3 ~ 0.5, and $p_0/\rho gh$: 0.03 ~ 0.1. These values are used in the subsequent discussion.

Significant factors in the wave dissipation by the flexible mound are found to be 1) interaction between radiation waves and scattering waves, 2) breaking waves over the structure, and 3) energy loss other than the breaking waves. Since the mechanism of the energy loss has not been analyzed in detail, the first two factors are investigated by comparison with the characteristics of wave dissipation by a rigid breakwater. Fig.7 shows the numerical results of the transmission and the reflection coefficients, K_T and K_R, versus the parameter, B/L, for the rigid and the flexible models. The flexible mound can markedly reduce the transmitted wave heights because of the phase interaction between the radiated and diffracted waves, whereas the transmission coefficient is nearly 1.0 in the case of the rigid model. In Fig.7, there

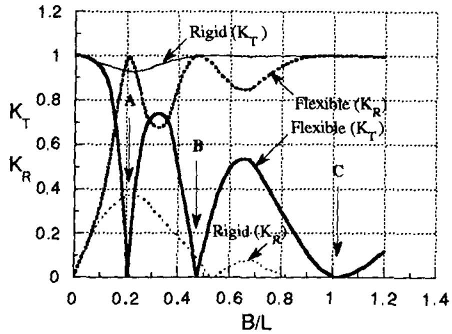

Fig.7 Comparison of K_T characteristics between for a rigid model and a flexible model

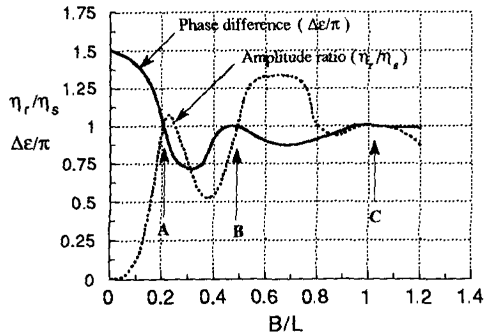

Fig.8 Amplitude ratio and phase differences of radiation wave to scattering wave.

are wave periods, A, B and C, at which K_T =0.0. At these points, the scattering and the radiation waves have the same height but are in the inverse phase as seen in Fig.8. Thus, it is concluded that the phase interaction between the radiation and the scattering waves plays the primary role for wave dissipation by the flexible mound. The points where no waves transmit may be related to the natural periods of the flexible mound.

Fig.9 shows the experimental results of K_T versus B/L for the rigid and the flexible models under breaking wave conditions. The parameters, R/H_I and B/L, are important for the wave dissipation for the rigid model. As is well-known, when R/H_I is greater than 2.0 or B/L is less than 0.3, a rigid model cannot reduce the transmitted wave heights because the incident waves propagate over the structure without breaking (Nagai et al., 1977). The breaking waves may also play an important role in wave dissipation by flexible dikes when R/H_I is small. As shown in Fig.9, however, the characteristics of wave dissipation for the flexible model are different from those for the rigid model under the condition of wave breaking. This indicates that the transmitted waves for the flexible model may be reduced not only by the wave breaking but also by the wave interaction.

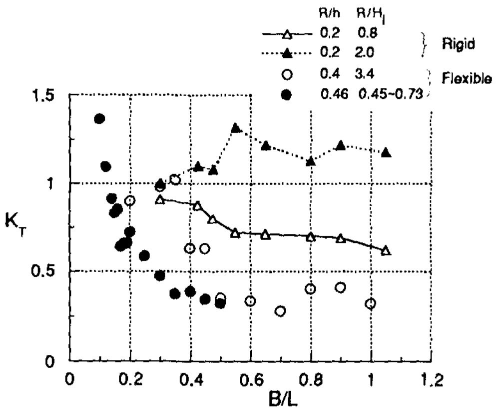

Fig.9 Effect of wave breaking on transmission coefficients by experiments (Case A - 2 : R/h = 0.4, B/h = 2.34, $p_0/\rho gh$ = 0.5, Case B - 1 : R/h = 0.46, B/h = 2.29, $p_0/\rho gh$ = 0.5, Case C - 1 : R/h = 0.2, B/h = 3.56)

Since a flexible mound is a kind of multi-degree-of freedom oscillation system, it is expected to respond sensitively to the wave periods. Therefore, it is important for practical design of the flexible breakwater to evaluate the effects of irregularity of wave field on the wave dissipation. Fig.10 shows the experimental results for regular and irregular waves for which the incident wave heights, H_I and $H_{1/3}$, are 8cm and between 6.2 and 8cm, respectively. Bretschneider-type spectra (Bretschneider, 1968) , with the significant periods, 1.24, 1.43 and 1.63, were used for irregular waves. The performance of K_T for irregular waves is insensitive to B/L compared to the results for the regular waves, a desirable feature for practical applications.

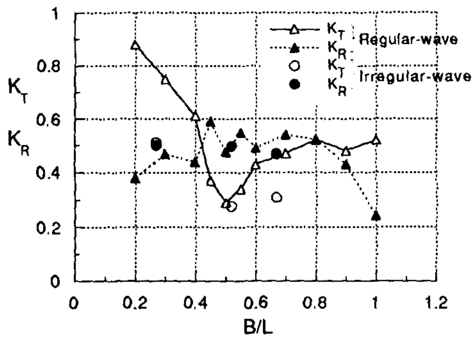

Fig.10 Comparison between regular & irregular waves (exp.)

Utility and Application of the flexible mound

A prototype model of the flexible mound, which has a 4 m-wide base and is 1.2 m high, was designed according to the aforementioned experimental and numerical studies. The layout of the setup is shown in Fig.11. Experimental study was carried out to verify the effectiveness of wave control, the durability of the membrane, and the stability of the seabed around the structure under the conditions; h = 2 m, R/h = 0.4, $p_0/\rho gh = 0.05$ and B/h = 2.0. Fig.12 indicates an example of the characteristics of K_T versus B/L when R/H_I varies from 0.89 to 3.1. The prototype model achieved transmission coefficients of less than 0.5 in broad ranges of R/H_I and B/L. Figs.13 and 14 show experimental results of scoring around the structure and evolution of beach profile behind the structure. The maximum depth of scoring around the structure is about 30% of incident wave height even under storm surge condition, an insignificant factor in general application. The evolution of beach profile behind the flexible mound is also the same level as those of conventional submerged breakwaters. The durability of the membrane and the stability of the structure's base have also been verified in this experiment.

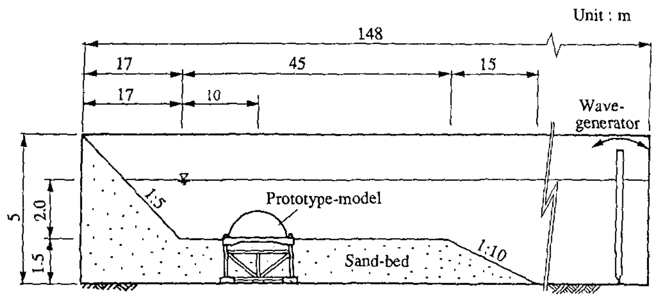

Fig.11 Layout of prototype model test

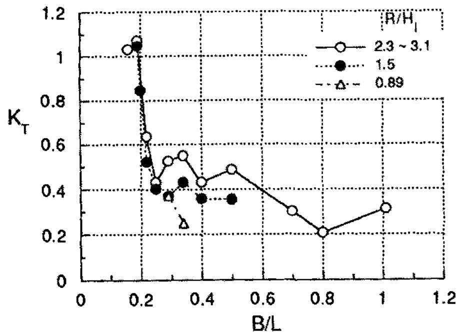

Fig.12 Wave transmission characteristics by a prototype model
(B/h = 2.0, R/h = 0.4, $p_0/\rho gh$ = 0.05)

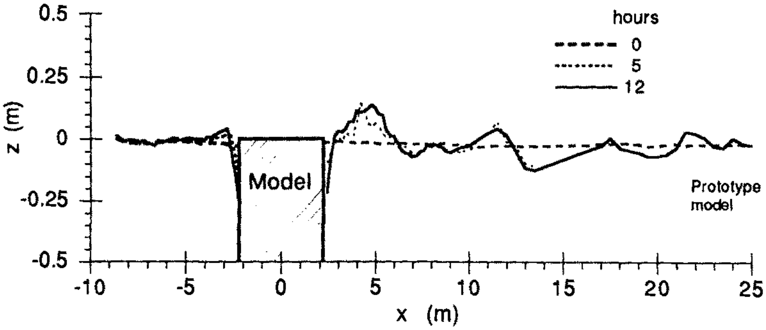

Fig.13 The scoring profile around the flexible mound

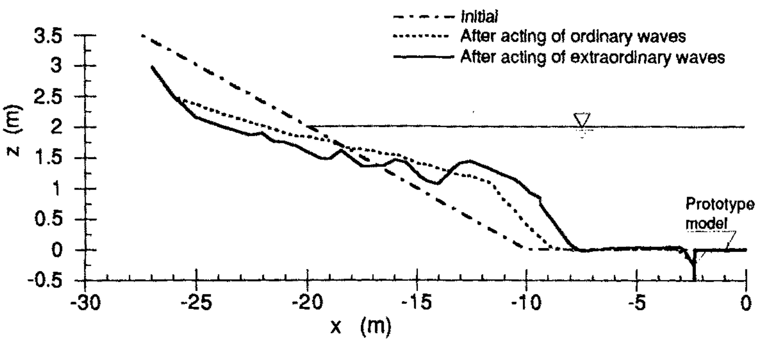

Fig.14 The evolution of the beach profile behind the flexible mound

The flexible mound is not only useful as an improved alternative to the ordinary submerged breakwaters but is also effective as an emergency breakwater, that can be inflated only during a storm passage. Two units of the flexible mound, 9 m wide, 40 m long and 3 m high, have been installed recently at an entrance of a small harbor shown in Fig.15. The units are normally deflated, flush with the sea floor with water-supply-drainage system so that passenger liners can pass over the structure. During a storm surge, the mounds are inflated by the water and serve as emergency breakwaters. Photo.1 shows a inflated membrane at a construction yard. Before the installation, it has been verified by 3-dimensional model tests that the flexible structures can reduce transmitted wave heights to less than 50 % of incident wave on average.

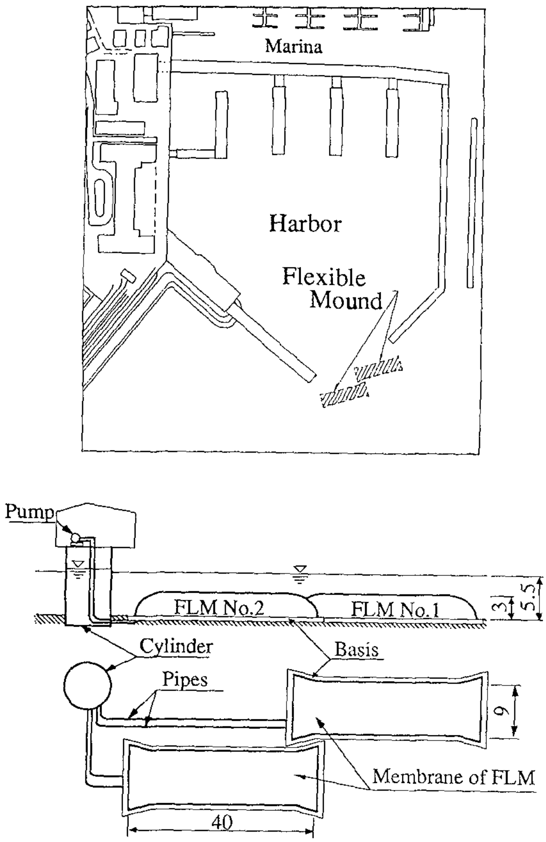

Fig.15 The equipments and their layout of the applied flexible mound as an emergency breakwater

Photo 1 Inflated Membrane

Conclusions

A flexible submerged breakwater, composed of a thin membrane bag filled with water, has been developed for wave control in shallow water as an alternative to the conventional rigid type. The flexible dike can be made more compact compared to the rigid type, and controls waves without sacrifice to the scenic value of the coastal landscape. A noteworthy feature of the flexible design is that it utilizes the interaction of incident and scattering waves with radiation waves generated by the membrane's motion.

Major findings are summarized as follows:

(1) Three factors, 1) wave interaction, 2) wave breaking over the structure and 3) energy loss other than breaking waves, are related to the mechanism of wave dissipation by the flexible breakwater. The interaction of the scattering waves with the radiation waves, generated by the membrane's motion, plays the most important role in wave dissipation. The performance of the wave interaction is effective when the scattering and the radiation waves have the similar height but in the inverse phase. In addition to the interaction, the wave breaking is also important for the dissipation of the wave energy when the crown depth to incident wave height, R/H_I, is small. The energy loss excluding wave breaking also has some significance. Its mechanism is currently being investigated by writers.

(2) Although the flexible dike consists of a multi-degree-of freedom oscillation system, characteristic of wave dissipation for irregular waves is not sensitive to wave periods.

(3) The effectiveness of wave dissipation by the flexible mound, the durability of the membrane and the stability of the structure were verified by a prototype model test for a wide range of wave conditions.

(4) The flexible mound is not only useful as an improved alternative to the conventional submerged breakwaters but is also effective as an emergency breakwater, that can be inflated only during a storm passage. Two units of flexible mound have been installed at an entrance of a harbor as a emergency dike, recently.

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