EFFECTIVENESS OF A RESONATOR UNDER WAVE BREAKING AND NON-WAVE BREAKING CONDITIONS FOR SHELTERING A HARBOR

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台風などによるうねり性の外洋波浪が作用する厳しい条件下において，港内おける静穏度の確保を目的として，港口部に波浪共振装置を設ける工法の有効性を理論と実験により検討した。実験では，従来において明確にされていない，砕波が生じるときの共振装置の効果を非砕波の状況を含めて明らかにした。このとき，理論的な効果の予測を目的として，回折効果を重視した数値解析法および水深変化による屈折効果をも考慮した解析法の両者による算定を行い，実験結果との比較を行った。

Key Words: *Resonator, Wave filter theory, Harbor tranquility, Wave breaking, Numerical predictions*

1. INTRODUCTION

Performance of a low reflective wave resonator has been examined to shelter the model harbor from stormy wave conditions, such as swells driven by typhoons. The effectiveness of a rectangular resonator with low reflective walls in the case of wave breaking conditions as well as non-wave breaking conditions has been tested experimentally. Theoretically predicted performance of the resonator has been extensively compared with the experimental results for the given wave conditions especially under the influence of wave breaking.

The site condition of the proposed harbor is too harsh to construct the conventional breakwater system. It may be uneconomical and extremely difficult to accomplish the harbor breakwater system. The installation of the low reflective wave resonator is considered as one of effective ways to provide the sufficient tranquility with the model harbor economically. Mochizuki & Mitsubashi[1)] proposed the Wave Filter Theory for designing resonators by employing the theory of the electric circuit filter. The theory has been followed by the studies on the resonators with various configuration models and well proved for the sheltering effect (Nakamura et al. [2), 3)]).

In this study, by referring carefully to the previous experimental results on the wave resonators by Nakamura et al. [2),3)], the possible wave resonator for the corresponding site conditions was designed based on the Wave Filter Theory. An experimental model of 1/100 scale of the harbor was constructed in the large wave tank as detailed as possible to represent the actual topographic configuration of the proposed harbor. The wave refraction due to depth variations of the harbor, thereby, can be considered in this model test. To maintain the existing entrance channel and also to obtain the better sheltering effect, two arrangement options of the resonator were chosen; one was installed inside the harbor and the other outside the harbor.

2. RESONATOR DESIGN

(1) Outline of the wave filter theory

Wave filter theory was developed by Mochizuki & Mitsubashi[1)]. The fundamental concept of this theory is to use the similarity between a water wave resonator and its equivalent electric circuit.

By applying this theory, the basic shape of the proposed resonator can be determined from the following set of equations.

$$l_1 = \frac{m\sqrt{gh}}{2\pi f_C} \quad (1)$$

$$b_1 = \frac{m b_0}{\sqrt{2(1-m^2)}} \quad (2)$$

$$l_2 = \frac{\sqrt{2(1-m^2)}}{m} l_1 \quad (3)$$

$$m = \sqrt{1-\left(\frac{f_C}{f_\infty}\right)^2} \quad (4)$$

where, f_C: cut off frequency; and f_∞: pole frequency, and definitions of other variables are specified in **Fig.1**.

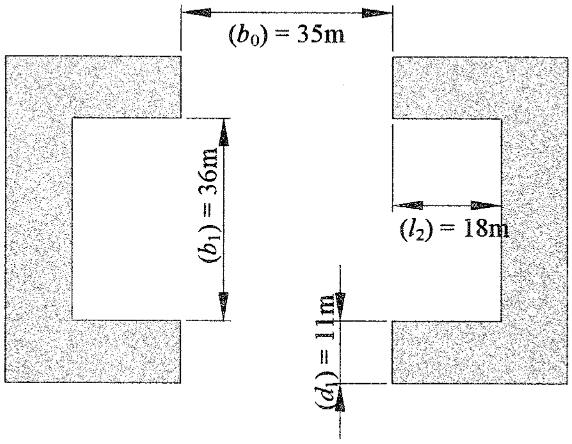

Fig.1 Basic shape of the resonator.

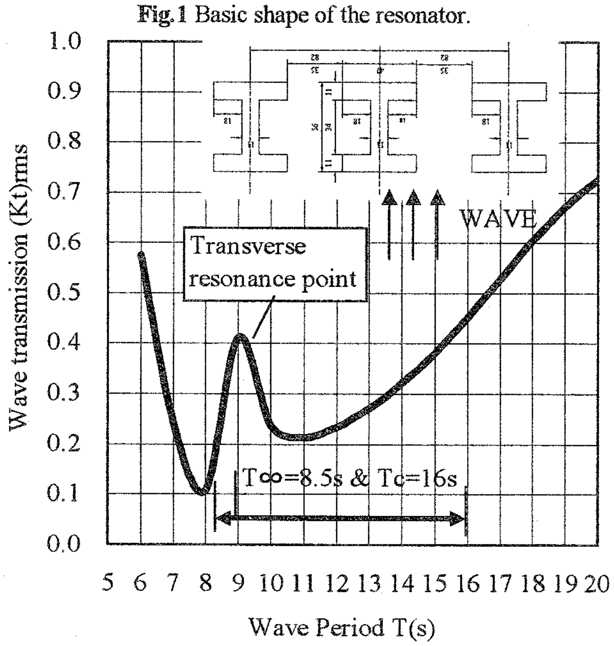

Fig.2 Wave transmission characteristics through an array of rectangular resonators designed by wave filter theory.

Table 1 Design wave conditions.

	Prototype		Model (1/100)	
	$T_{1/3}$(s)	$H_{1/3}$(m)	$T_{1/3}$(s)	$H_{1/3}$(cm)
Extreme Waves	14	11	1.4	11
Nominal Waves	7	3	0.7	3

(2) Dimensions of the proposed resonator

The design wave conditions at the site are listed in **Table 1**. The extreme wave condition is very hard because the harbor faces to the Pacific Ocean directly. Taking both the extreme and nominal wave conditions into account, dimensions of the resonator adequate at the site were determined by using the above equations. The opening length of a resonator b_0 is set to be roughly equal to the harbor entrance width at the site, i.e. b_0=35m. And the water depth h=9m is adopted, which corresponds to the water depth of inside harbor.

A proposed resonator is shown in **Fig.1** with dimensions b_1= 36m, l_2=18m, and d_1= 11m was obtained by applying the wave filter theory for the most possible cutoff frequency of the wave period 16s and pole frequency of the wave period 8.5s for the water depth h=9m.

Then the validity of the proposed resonator was checked by the infinite array method. In this method the infinite number of the proposed resonator is arranged in line perpendicular to the incident wave direction (as shown in **Fig.2**) and the root mean square value of the transmitted wave energy, Kt(rms) is calculated. The result is shown in Fig.2. It is seen that the proposed resonator is well effective within the range of the wave period 8s and 16s with the Kt(rms) value lower than 0.4.

Finally the resonator was installed at the harbor by adjusting to fit the layout of the harbor. According to the topographic condition of the harbor, keeping the existing waterway, two options of the resonator were chosen; one was installed inside the harbor and the other outside the harbor.

3. THEORETICAL CALCULATION & EXPERIMENT

Three harbor models were chosen for the theoretical calculation and experiment;

(a) the original harbor (**Fig.3**),

(b) the harbor with the resonator installed inside the harbor (**Fig.4**),

(c) the harbor with the resonator installed outside the harbor (**Fig.5**).

(1) Theoretical calculation method

We have used two different theoretical approaches; one is accounting for only wave diffraction effects with the assumption of constant water depth and the other the combined refraction and diffraction effects to account for water depth variations and wave breaking phenomena. The former approach is the vertical line source Green's function method (VLG)[4]. The latter is based on the unsteady mild slope equation (UMSE) by Watanabe et al[5]. Various wave conditions, including obliquely incident waves were considered in the theoretical analysis.

For irregular waves, the discretization technique of the target continuous frequency spectrum proposed by Goda[6] was first applied. The linear superposition principle of discretized component wave energy was then used to estimate the significant wave height at the given point. For irregular waves, only the constant depth analysis based on the VLG method was used for simplicity.

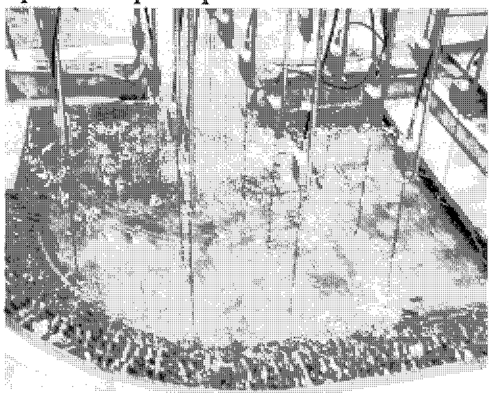

Fig.3 Original harbor.

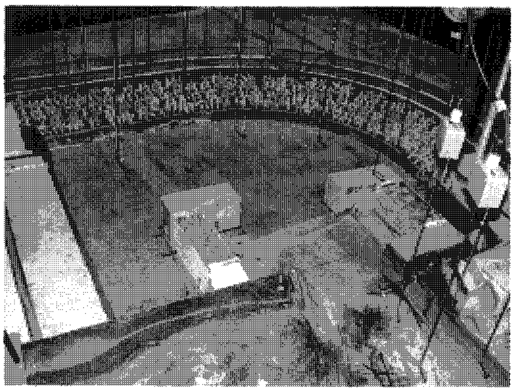

Fig.4 Inside resonator.

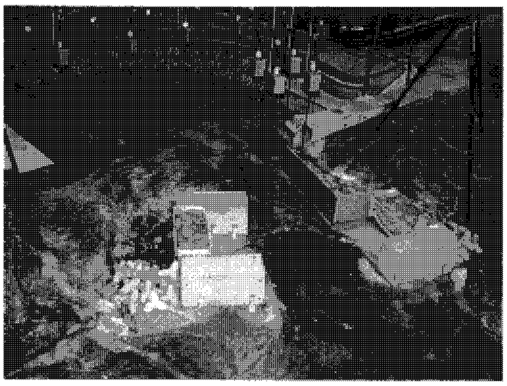

Fig.5 Outside resonator.

(2) Experiment

Fig.6 shows the topographic map of the original harbor. The map is based on the chart datum level (CDL). The water level adopted here is corresponding to HWL, which is 2.5m above the CDL.

A very large wave basin of width 20.5m and length 37.5m was used for the model test. The multi-directional and irregular wave maker was installed at the end of the basin.

In this experiment, the incident wave angle as shown in **Fig.6** was adopted, which corresponds to

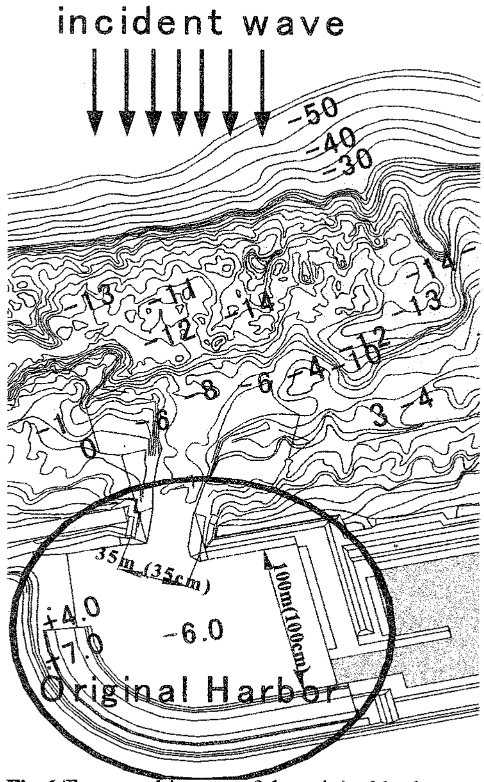

Fig.6 Topographic map of the original harbor.

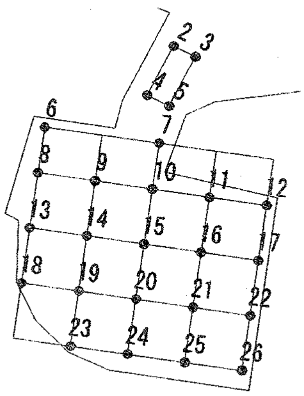

Fig.7 Arrangement of the wave gauges.

the direction parallel to the waterway at the harbor entrance. The water depths in the harbor area and in front of the wave generator board were 9cm and 59cm respectively. The wave height distributions around the harbor model were measured at grid points as shown in **Fig.7**. The spacing between the wave gauges is 30cm.

Low reflective walls were used for the inner side of the resonator as a countermeasure for the standing wave excited in the resonator. Other marginal boundary in the harbor was partly covered with low reflective materials for realizing dissipative dikes.

Breaking waves and non breaking waves were generated for the regular wave conditions while only the situation under the influence of wave breaking was adopted in the case of irregular wave. The wave conditions of the experiment are summarized in **Table 2**.

Table 2 Wave conditions of the experiment.

Run	T (s)	H_0 (cm)	Wave Condition	Wave Type
1	0.7	3.0	Non breaking	Regular
2	0.9	3.0	Non breaking	Regular
3	0.9	8.0	Breaking	Regular
4	1.1	3.0	Non breaking	Regular
5	1.3	3.0	Non breaking	Regular
6	1.3	6.0	Breaking	Regular
7	1.5	3.0	Non breaking	Regular
8	1.7	3.0	Non breaking	Regular
9	1.7	6.0	Breaking	Regular
10	1.0	6.0	Breaking	Irregular
11	1.2	6.0	Breaking	Irregular

4. THEORETICAL & EXPERIMENTAL RESULTS

The theoretical results obtained by the different numerical analysis are categorized in the following figures and tables;

i)VLG method

- Result for regular waves is labeled in figures as **cal.(regular)**
- irregular wave is labeled in figures as **cal.(irregular)**

ii)UMSE method (regular wave only)

- wave breaking condition assuming H_0=6cm or larger in the model scale is labeled in figures as **cal.UMSE wave break(regular)**
- non wave breaking condition is labeled in figures as **cal.UMSE non wave break(regular)**

(1) Result for regular waves

Figs. 8 to 10 show the average wave height ratio in the harbor basin excluding the resonator and harbor mouth areas for regular waves. The wave height ratio is defined as a ratio of wave height at the designated point to the incident wave height in the offshore.

The theoretical results by UMSE method shows little or no significant difference from those obtained by VLG method in the case of harbor with resonators inside and outside as seen in **Fig.9** and

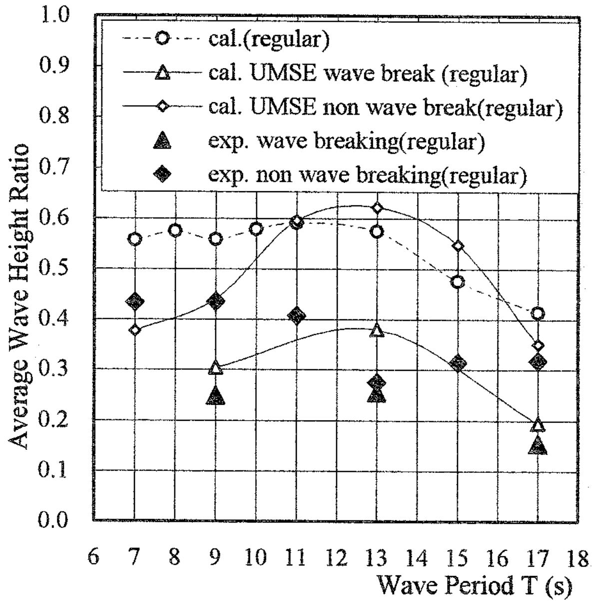

Fig.8 Average wave height ratio in the harbor basin (original harbor).

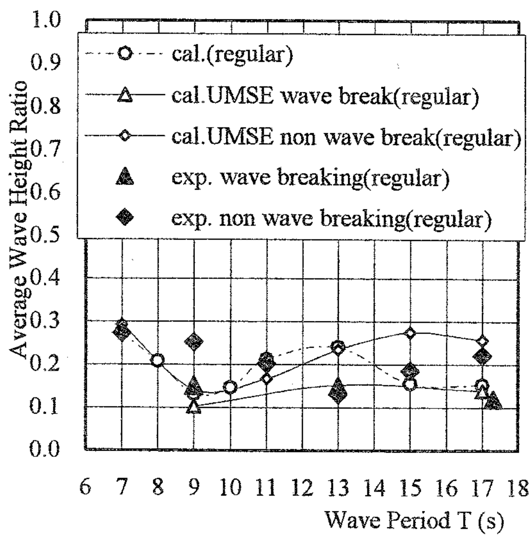

Fig.9 Average wave height ratio in the harbor basin excluding resonator region (inside resonator).

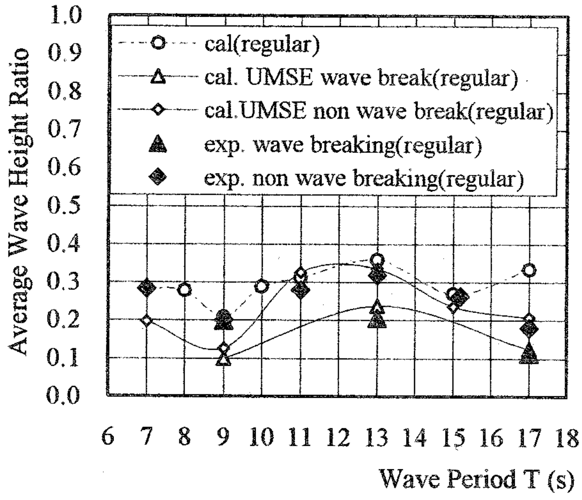

Fig.10 Average wave height ratio in the harbor basin (outside resonator).

Fig.10, respectively. Furthermore, we can see comparatively good agreements between the experimental and theoretical results for either non-breaking or breaking wave conditions with respect to the cases of harbors with resonators. UMSE seems to be more useful than VLG because it is able to account for wave energy dissipations due to wave breaking.

In the case of original harbor, however, the experimental results on the wave height ratio are comparatively lower than the theoretical ones (see **Fig.8**), especially for non breaking wave conditions and longer waves. It may be considered that the higher energy dissipation in the harbor appears for the experiment.

From the comparisons among **Figs.8 to 10**, it is clear that the resonator is very effective to protect the harbor basin from stormy incoming waves. It is also seen that the resonator is still active for high waves, such as breaking or nearly breaking waves at the harbor entrance.

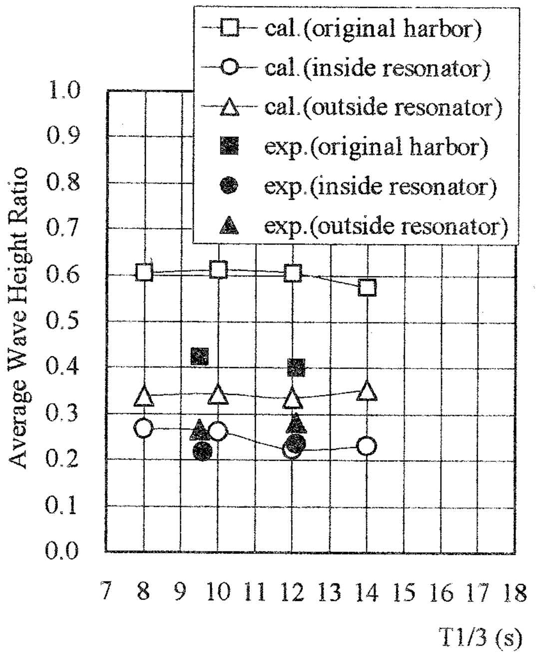

Fig.11 Average wave height ratio in the harbor basin (irregular wave).

(2) Result for irregular waves

Fig.11 shows the result on the average wave height ratio in the harbor basin for irregular waves. In the figure, the calculation result by VLG is also shown. It can be seen that there is a comparatively large difference between the measured and calculated results especially for the result of the original harbor case. It may be caused by the fact that the VLG analysis ignores the energy loss due to wave breaking.

It can be seen that the resonator is effective not only for regular waves but also for irregular waves. Effectiveness of the resonator for irregular waves in this experiment is similar to that of the case of regular waves of non-breaking waves.

From the above total comparisons, the resonator installed inside the harbor seems to be more effective for sheltering the harbor basin.

5. WAVE HEIGHT DISTRIBUTION

Figs. 12 to 14 show the calculation results on wave height distribution around the harbor under the condition of wave breaking; T=0.9s, the period of which the resonator shows its most effective characteristic (see **Fig.9** and **Fig.10**) and, H=8cm, (in prototype T = 9s, H= 8m). The UMSE was employed to be able to account for wave energy dissipation due to wave breaking.

We can reconfirm that the resonator installed either inside or outside of the harbor is effective to tranquilize the harbor basin from stormy incoming waves. It is also seen that the wave height in the resonator basin is not so high as compared with the

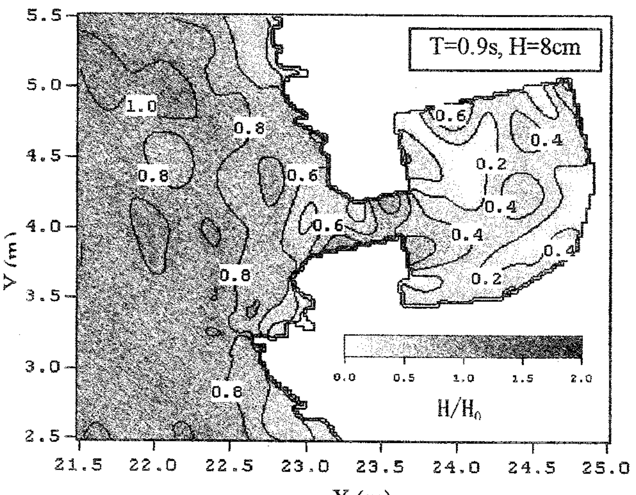

Fig.12 Wave height distribution (original harbor).

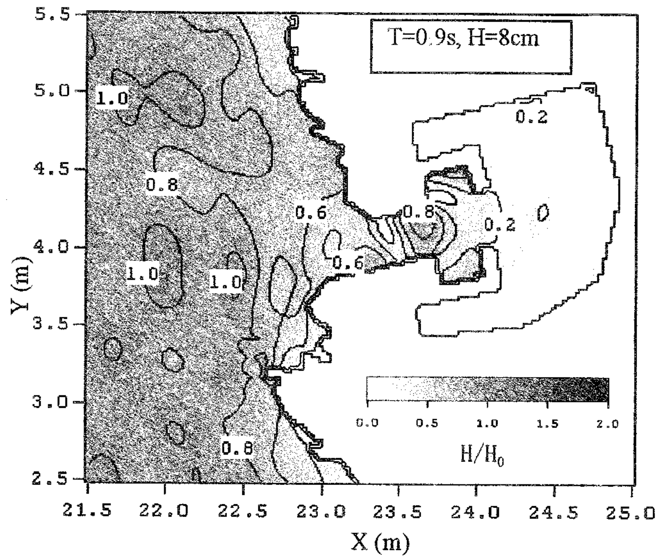

Fig.13 Wave height distribution (inside resonator).

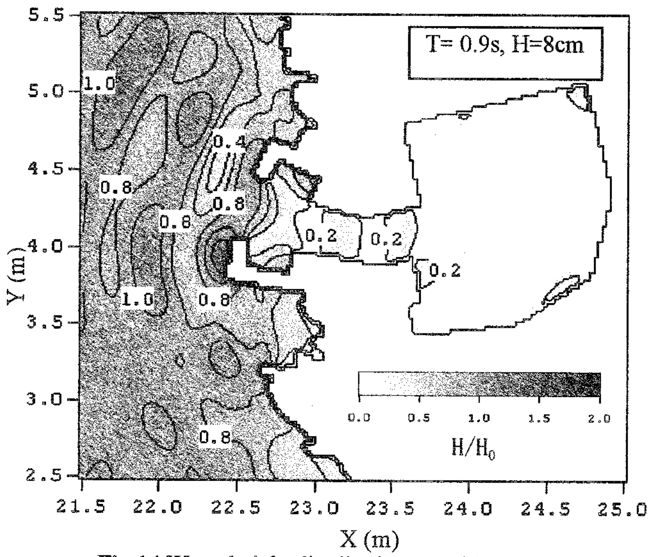

Fig.14 Wave height distribution (outside resonator).

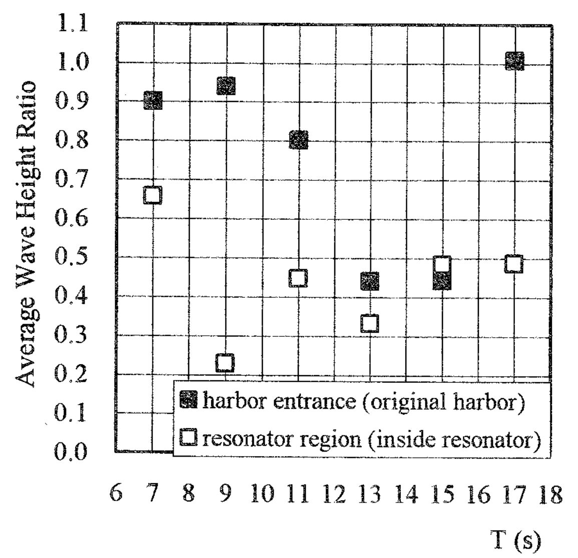

Fig.15 Wave height ratios in the resonant basin (inside resonator case); comparison with those at the entrance channel of the original harbor.

wave height at the harbor entrance channel of the original harbor. Apparently, in the account of the harbor entrance, the case of outside resonator is most effective because the entrance channel to the harbor is also tranquilized by the resonator in addition to the harbor basin.

Fig.15 shows the experimental result on the average wave height ratio in the resonant basin for the case of inside resonator. In the figure, for the comparison, the average wave height ratio at the harbor entrance channel of the original harbor is also plotted. From the figure, we can see that the wave height in the resonant region is comparable to that of the entrance of the original harbor. In some wave period conditions, the wave height in the resonant region is smaller than the original one.

6. CONCLUSION

The resonator is effective for sheltering the harbor basin from stormy waves even though incident waves breaks near the harbor entrance. The resonator installed inside the harbor is generally more effective than the one outside the harbor. Moreover, because of the stormy wave conditions, the installation of the resonator inside the harbor may be much easier and more economical than the outside one.

It is also confirmed theoretically that the resonator is effective to reduce incoming waves to a harbor. The unsteady mild slope equation method is more useful for the prediction of the resonator performance than the constant depth analysis such as the vertical line source Green's function method.

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