CHAPTER 92

Hydraulic Characteristics and Field Experience of New Wave Dissipating Concrete Blocks (ACCROPODE)

Masanori Kobayashi¹, Sumio Kaihatsu¹

ABSTRACT

More than 30,000 pcs. of the ACCROPODE blocks have been applied for the wave dissipator of the breakwaters and the revetments at the Haramachi thermal power station where construction works of the harbor started about four years ago.

Since the ACCROPODE has not been used in Japan beforehand, hydraulic model tests were needed to examine its characteristics and to confirm the feasibility to the project, although extensive tests have been made in the world.

This paper describes the results of tests on the stability, reflection and transmission coefficients of the ACCROPODE blocks and the field experience at the Haramachi power station. Much reduction of the construction costs and good stability against storm waves attacked were obtained which showed its super usage as the wave dissipator.

INTRODUCTION

Tohoku Electric Power Company in Japan is now constructing the Haramachi thermal power station. This power station has 2 units of 1,000 MW coal fired thermal power plants, and a port facility capable of mooring a 60,000 DWT class coal carrier ship (Fig.1).

The total length of breakwaters and of revetments are 3.0 kms and 2.5 kms respectively. For the breakwaters two types were employed, one is the rubble-mounded type of 0.7 kms long for the coast shallower than 10 meters and the other is the caisson composite type of 2.3 kms long for the

1. Civil Engineering Dept., Tohoku Electric Power Co., Inc. 3-7-1 Ichiban-cho Aoba-ku Sendai 980, JAPAN

1269
deeper zone than 10 meters. Selection was made mainly by the reason of construction costs.

Since 1984 until 1989 the staff members of the civil engineering department of Tohoku Electric Power Company had continued the contact with SOGREAH on the ACCROPODE blocks to be used for the mound of breakwaters and revetments because of the high stability, the financial benefit and the easy construction method. Final decision of employing the ACCROPODE was made through the hydraulic model tests conducted independently by the company itself which confirmed the preceding tests in the world with the detailed data of the reflection and transmission coefficients not supplied beforehand.

This paper describes the results of the tests and the field experience of the Haramachi project exposed to the ocean storm waves up to date without any harm.

**DESCRIPTION OF TESTS**

*Experimental Equipment*

The wave flume in which the model tests were conducted, is shown in Fig.2. It is a two dimensional wave flume, 34 meters long, 5 meters wide, and 1.2 meter deep. The scale was 1:50, following the Froude similarity. The foreshore slope was uniform with 1:100, simulating the sea bottom of the Haramachi field. The tests were carried out by waves generated with the power spectra of the Bretschneider-Mitsuyasu type.
Test Conditions

The cross section of the rubble-mound breakwater model is shown in Fig. 3. The test conditions are shown in Table 1. More than 20 tests were conducted under various combination of these conditions which are probably expected in the project site.
Table 1 Test Conditions

<table>
<thead>
<tr>
<th></th>
<th>Model</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth</td>
<td>20 cm, 30 cm, 40 cm</td>
<td>10 m, 15 m, 20 m</td>
</tr>
<tr>
<td>at the structure</td>
<td>1.2 sec, 1.7 sec</td>
<td>8.5 sec, 12.0 sec</td>
</tr>
<tr>
<td>Wave period</td>
<td>2.0 sec, 2.3 sec</td>
<td>14.1 sec, 16.3 sec</td>
</tr>
<tr>
<td>Armour layer (ACCROPODE)</td>
<td>74.0 g, 166.3 g</td>
<td>9.3 t, 20.8 t</td>
</tr>
<tr>
<td>Filter layer (gravel)</td>
<td>20-30 g</td>
<td>3-4 t</td>
</tr>
<tr>
<td>(γŁ block)</td>
<td>32.8 g, 73.6 g</td>
<td>4.1 t, 9.2 t</td>
</tr>
<tr>
<td>Core (gravel)</td>
<td>0.5-4 g</td>
<td>50-500 kg</td>
</tr>
</tbody>
</table>

The ACCROPODE blocks were installed in the armour layer, and two types of the ACCROPODE blocks, 74.0 g and 166.3 g, were used.

In the filter layer, gravels and two types of the γŁ blocks 32.8 g and 73.6 g were used. The γŁ block is the artificial concrete block, used in lieu of the large rubble stone.

The core was made of gravels which weight was from 0.5 g to 4 g equivalent to 50 kgs to 500 kgs in the field.

The slope of armour face was fixed as 1:1.33 as shown in Fig.3. Owing to the report by CSIR (Holtzhausen and Zwamborn, 1991, Ref.1), the 1:2 slope was more stable than the 1:1.33 slope and the 1:1.5 slope but the rocking displacement before the failure was more remarkable than the latters. On the other hand interlocking by the initial shake down causes units to pack more densely for the 1:1.33 slope while units do not pack much closer during shifting on a flat slope. This was the main reason of this slope which was strongly recommended by SOGREAH.

The tests were carried out with three types of the water depth at the structure, from 20 cm to 40 cm deep, and four types of the significant wave period, from 1.2 sec to 2.3 sec.

In the Haramachi project, design conditions are as follows that the maximum water depth at the breakwater is 10 meters, equivalent to 20 cm in the model, and the design wave period for the significant wave is 16 sec, equivalent to 2.3 sec in the model.

In each cases the crest height of the model above the sea level was 11 cm, equivalent to 5.5 meters in the field.

Arrangement of the ACCROPODE

The arrangement of the ACCROPODE in the tests is shown in Fig.4. The centers of gravity of each block are plotted in white and black, where H is the height of the block.

The horizontal spacing is 1.24H along horizontal lines, and the distance between each horizontal lines is 0.6H. The thickness of the armour layer is 0.9H.
Definition of damage

In order to estimate the stability of the ACCROPODE, the damage ratio of the armour layer is defined as follows.

\[ D = \left( \frac{n}{N} \right) \times 100 \quad (1) \]

where,
- \( D \): the damage ratio (%)
- \( N \): the total number of blocks in the test area
- \( n \): the actual number of blocks displaced more than the height of the block

The definition of the test area is shown in Fig.5. The area, from 1.5Hs (Hs: significant wave height) below the still-water level to the crest of the model, and 1.0 meter wide, is the test area. In this test area from 200 pcs. to 300 pcs. of the ACCROPODE blocks were included. According to this definition, 2% of the damage ratio is nearly equivalent to the condition of severe damage.
RESULTS OF TESTS

**KD and Ns values**

The damage ratio D versus KD and Ns values are plotted in Fig.6. The KD value is the Hudson stability factor. The Ns value is the stability number given by the following relation with the KD value.

\[
Ns = \frac{Hs}{\Delta Dn} = (KD \cdot \cot \alpha)^{1/3}
\]  

where,

- \(Hs\): significant wave height in front of the structure
- \(\Delta\): relative mass density of the unit
- \(Dn\): nominal diameter of the unit
- \(\alpha\): slope angle of the structure

In these figures the filter layer is composed of gravels.

At 0% of the damage ratio, the KD value is estimated in the range of 30 to 50, from 3.5 to 4.0 equivalent in the Ns value. From these KD or Ns value, it can be said the initial stability of the ACCROPODE, in other words the stability against the start of damage is very high compared with the other artificial armour units.

In the region under 2% or 3% of the damage ratio, the Ns value increases with the rate much higher than that of the damage ratio. But in the region over 2% or 3% of the damage ratio, the Ns value scarcely increases with the increase of the damage ratio. The Ns values at the condition of no damage and severe damage (or failure) are very close with each other. This means that the structure fails progressively after damage started.
All the tests carried out under the design condition of water depth at the structure (20 cm in the model) in the Haramachi project, could be found no damage at all.

**Influence of the wave period**

The Iribarren number, or the surf similarity parameter \( \xi_z \) is defined as,

\[
\xi_z = \tan \alpha / (H_s / L_o)^{0.5}
\]  

where \( L_o \) is the deep water wave length derived by the wave period with zero up-crossing. Fig.7 shows the relation between the \( N_s \) values and the surf similarity parameter \( \xi_z \) where the damage ratio is 0% or 2%. The filter layer is composed of gravels. In our tests, \( \xi_z \) was in the range of 3 to 5.

In case of 0% of the damage ratio, even though the data is scattered, the \( N_s \) value has a tendency to decrease with the increase of \( \xi_z \). And in case of 2% of the damage ratio, such tendency is not so remarkable in compare to the cases of 0% of the damage ratio. We could find the influence of the wave period in case of the gravel filter.

In case of the \( \gamma \ell \) blocks used for the filter layer, the relation between \( \xi_z \) and \( N_s \) is shown in Fig.8. From this figure, the influence of the wave period is not found.
Fig. 7 Stability of The ACCROPODE
(Filter Layer : Gravel)

\[ N_s = \frac{H_s}{\Delta D_n} \]

\[ \xi_s = \tan \alpha / \sqrt{H_s / L_o} \]

- \( \bullet : D = 0\% , \quad \square : D = 2\% \)

(Filter layer : gravel)

- \( \bigcirc : D = 0\% , \quad \square : D = 2\% \)

(Filter layer : \( \gamma \ell \) block)
Effect of the filter layer's material

From Fig. 7 and Fig. 8, it is found that the difference of the filter layer's material, gravels or the γℓ blocks, has the influence on the stability of the armour layer. At the condition of no damage, the KD value will be estimated in the range of 30 to 50 in case of the gravel filter, showing higher stability than in case of the γℓ block's filter in which case the KD value will be at only 20.

It could be estimated to choose the most favorable weight (or size) of the γℓ blocks for the weight of the ACCROPODE units. However such relationship was not recognized since the uneveness of the filter setting seemed to be another origin of data scattering.

Comparison of results with other investigations

Fig. 9 shows the comparison of results with other investigations, carried out by SOGREAH (Perdreau, 1983, Ref.4) and DELFT hydraulics laboratory (Van der Meer, 1987, Ref.2). Although the influence of wave period was found in case of the gravel filter, our present studies show similar results and tendency of the Ns value to other investigations.

It should be noted that the difference of the stability number between no damage and severe damage is very much small where \( \xi_z \) was 3 and increases with the increase of \( \xi_z \). Holtzhausen and Zwamborn (Ref.1) gave caution that the time from start of damage to failure is shorter for steeper slopes.

\[
\xi_z = \tan \alpha / \sqrt{H_s / L_0}
\]

Fig. 9-1 Stability of The ACCROPODE by Different Investigations (at No Damage)
Reflection coefficient

The reflection coefficient $K_R$, as a function of the wave steepness is shown in Fig.10. All the data are distributed in the range of 0.25 to 0.6 of the reflection coefficient. It is found that the reflection coefficient increases with the increase of the water depth and the wave period. This tendency is similar to the characteristics of the other artificial armour blocks.

Transmission coefficient

Fig.11 shows the wave height transmission coefficient $K_T$, as a function of the wave steepness in case of 40 cm water depth at the structure. Under the same condition of the wave steepness, the transmission coefficient had a tendency to become larger when the wave period became longer. The transmission coefficient was highly affected by the wave overtopping. Under non-overtopping condition the transmission coefficient was less than 0.2, but when overtopping started it increased up to 0.4.

In Fig.12 the transmission coefficient are plotted as a function of the relative crest height $h_c/H_s$, where $h_c$ is the crest height above the sea level. In this figure, the typical curve of the transmission coefficient can be drawn.
Fig. 10 Reflection Coefficient vs. Wave Steepness

Fig. 11 Wave Transmission Coefficient vs. Wave Steepness
Design conditions

We decided the weight of the ACCROPODE blocks by the Hudson formula. The design wave height and the weight of the ACCROPODE are shown in Table 2.

In the Haramachi project, three types of the ACCROPODE blocks, 14.5 t, 20.7 t, and 27.6 t, are applied to the rubble-mound breakwaters and revetments. As the filter layer, 9 t type of the γ blocks are applied, mainly because of the difficulty of obtaining large stones as many as feeding to the site. The summation of these stones for the filter layer amounted to about 250,000 cubic meters.

The KD value of 10 was applied in our design. In case of the gravel filter, the KD value was estimated from 30 to 50 at no damage condition. But we reduced design KD value, considering the application of the γ blocks in the filter layer, the failure mode, the randomness of installed blocks especially below the sea level, and the unprecedented experience in Japan.

The KD value could be increased even up to 15.
WAVE DISSIPATING BLOCKS

Table 2 Design Conditions

<table>
<thead>
<tr>
<th>Water depth at the structure</th>
<th>2.0 m</th>
<th>6.0 m</th>
<th>8.0 m</th>
<th>10.0 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope angle (cot α)</td>
<td>1.25</td>
<td>1.33</td>
<td>1.33</td>
<td></td>
</tr>
<tr>
<td>Design significant wave height</td>
<td>4.9 m</td>
<td>5.9 m</td>
<td>6.7 m</td>
<td></td>
</tr>
<tr>
<td>ACCROPODE's weight (by Hudson formula)</td>
<td>10.8 t</td>
<td>18.9 t</td>
<td>27.6 t</td>
<td></td>
</tr>
<tr>
<td>ACCROPODE's weight (applied)</td>
<td>14.5 t</td>
<td>20.7 t</td>
<td>27.6 t</td>
<td></td>
</tr>
</tbody>
</table>

FIELD EXPERIENCE

Installation of the ACCROPODE

Total number of blocks which will be installed to the rubble-mound breakwaters and revetments, is about 12,000 pcs. in which about 11,000 pcs. were placed already.

In addition, we have a plan to place the ACCROPODE blocks, 9.2 t and 14.5 t, to the caisson-type composite breakwaters as armour units of the rubble foundation, and 3,000 pcs. have been already installed.

In the Haramachi project more than 30,000 pcs. of the ACCROPODE blocks will be installed in total.

Table 3 The 5 Highest Storm Wave Attacked

The Construction Site

<table>
<thead>
<tr>
<th>Maximum Wave</th>
<th>Date</th>
<th>Wave Height (m)</th>
<th>Wave Period (sec)</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1991. 2.16.</td>
<td>9.41</td>
<td>12.3</td>
<td>Low Pressure</td>
</tr>
<tr>
<td></td>
<td>1993.11.14.</td>
<td>8.36</td>
<td>9.5</td>
<td>Low Pressure</td>
</tr>
<tr>
<td></td>
<td>1993. 8.27.</td>
<td>7.60</td>
<td>12.5</td>
<td>Typhoon</td>
</tr>
<tr>
<td></td>
<td>1993. 3. 8.</td>
<td>7.39</td>
<td>11.0</td>
<td>Low Pressure</td>
</tr>
<tr>
<td></td>
<td>1994. 9.19.</td>
<td>7.05</td>
<td>12.5</td>
<td>Typhoon</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Significant Wave</th>
<th>Date</th>
<th>Wave Height (m)</th>
<th>Wave Period (sec)</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1991. 2.17.</td>
<td>5.52</td>
<td>15.8</td>
<td>Low Pressure</td>
</tr>
<tr>
<td></td>
<td>1993.11.14.</td>
<td>5.00</td>
<td>10.4</td>
<td>Low Pressure</td>
</tr>
<tr>
<td></td>
<td>1993. 3. 8.</td>
<td>4.94</td>
<td>10.8</td>
<td>Low Pressure</td>
</tr>
<tr>
<td></td>
<td>1993. 8.27.</td>
<td>4.61</td>
<td>10.9</td>
<td>Typhoon</td>
</tr>
<tr>
<td></td>
<td>1992.10.21.</td>
<td>4.11</td>
<td>10.2</td>
<td>Low Pressure</td>
</tr>
</tbody>
</table>
Experienced storm wave

About four years have passed since we began to install the ACCROPODE blocks. Table 3 shows the 5 highest storm wave conditions attacked the construction site after installation. But we have experienced no harm thus far. The stability of the ACCROPODE blocks in the field were very much excellent.

The highest wave was 9.41 meters in the maximum wave height and 5.52 meters in the significant wave height, which occurred on Feb. in 1991.

The design wave conditions at the point of the wave observatory, about 1.8 km offshore, are following: The significant wave height is 7.6 meters, the maximum wave height is 11.9 meters, and the wave period is 16 sec.

As shown in Fig.1, waves attacked obliquely which showed the excellent characteristics even tests were conducted in two dimensional conditions.

Results in the field experience

By applying the ACCROPODE blocks, the followings were recognized in the Haramachi project.
1) The area of the fabrication yard was rather small.
2) The moulding process was fairly easy, because of the simplicity formed by two symmetrical shells.
3) The settlement of blocks in the armour layer was almost completed in the range of 15 cm to 20 cm, after 7 days to 30 days following installation.
4) The void ratio of installed blocks was from 45% to 50%.
5) The strength of the block element was very high. Few or no blocks were broken.
6) The stability of the ACCROPODE in the armour layer against the wave force was good enough.
7) In comparison with other artificial blocks, quantity of concrete was saved about 30%, and the total construction costs for armour units, from production to installation to the rubble-mound breakwaters and revetments were reduced about 30%.

CONCLUSIONS

For the Haramachi project, the hydraulic model tests were carried out on the rubble-mound breakwaters armoured with the ACCROPODE blocks. The followings were observed as conclusions.

1) The stability of the ACCROPODE at no damage was very high, but the criteria of no damage and failure were very close.
2) The filter layer's material had an influence on the stability of the ACCROPODE in the armour layer. In case of the gravel filter, the KD value was estimated in the range of 30 to 50, but in case of the γL block's filter,
3) It was found that the wave period had an influence on the stability of the ACCROPODE in case of the gravel filter.

4) The reflection and the wave transmission coefficients were similar to the other artificial armour units.

Field experience showed successful achievement for the expense, the easy construction and the stability of the blocks.

ACKNOWLEDGEMENTS

The model of the ACCROPODE blocks were lent by SOGREAH, and their assistance is acknowledged with thanks.

REFERENCES