CHAPTER 92

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

Masanori Kobayashi[1], Sumio Kaihatsu[1]

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 before-
hand, 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 con-
structing 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

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1. Civil Engineering Dept., Tohoku Electric Power Co., Inc.
   3-7-1 Ichiban-cho Aoba-ku Sendai 980, JAPAN
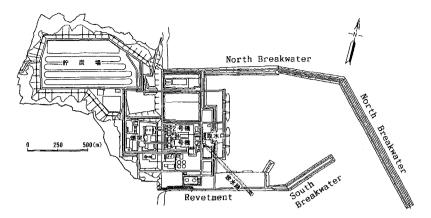
Fig.1 Plan View of The Haramachi Thermal Power Station

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-
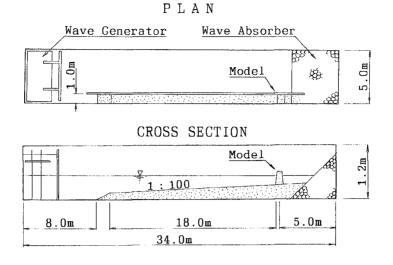Mitsuyasu type.

P L A N

Wave Generator   Wave Absorber

Model

Fig.2   Wave Flume

CROSS SECTION

Model

1 : 100

8.0m   18.0m   5.0m

34.0m

Sea Side   Harbor Side

180   Capping
      Concrete

42~60

1:1.33   Armour Layer

Filter Layer   70

Filter Layer

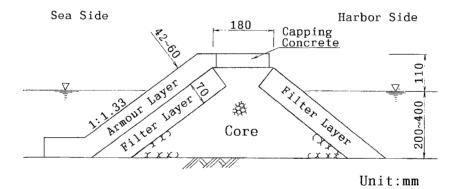Core

110

200~400

Unit:mm

Fig.3   Cross Section of Rubble-mound Breakwater Model

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

	Model	Field
Water depth at the structure	20 cm, 30 cm, 40 cm	10 m, 15 m, 20 m
Wave period	1.2 sec, 1.7 sec 2.0 sec, 2.3 sec	8.5 sec, 12.0 sec 14.1 sec, 16.3 sec
Armour layer (ACCROPODE)	74.0 g, 166.3 g	9.3 t, 20.8 t
Filter layer (gravel)	20-30 g	3-4 t
($\gamma\ell$ block)	32.8 g, 73.6 g	4.1 t, 9.2 t
Core (gravel)	0.5-4 g	50-500 kg

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 $\gamma\ell$ blocks 32.8 g and 73.6 g were used. The $\gamma\ell$ 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.
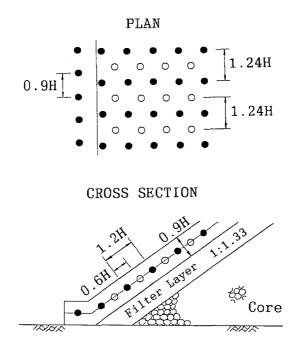
PLAN

CROSS SECTION

Fig.4   Arrangement of The ACCROPODE

Definition of damage

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

$$D = (n/N) \cdot 100 \tag{1}$$

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
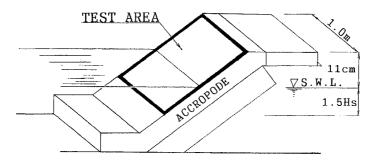nearly equivalent to the condition of severe damage.

Fig.5   Test Area

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.

$$Ns = Hs/\Delta Dn = (KD \cdot \cot \alpha)^{1/3} \qquad (2)$$

where,
   Hs: significant wave height in front of the structure
   Δ: relative mass density of the unit
   Dn: nominal diameter of the unit
   α: 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.
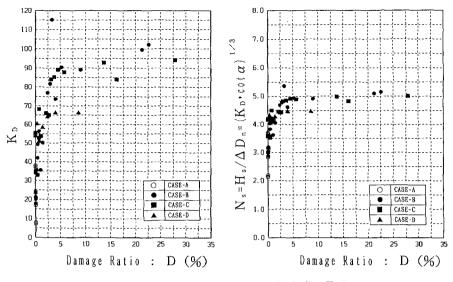
Fig.6   Damage Ratio vs. KD & Ns Values
        (Filter Layer : Gravel)

      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
ξz is defined as,

$$\xi z = \tan\alpha / (Hs/Lo)^{0.5} \qquad\qquad (3)$$

where Lo is the deep water wave length derived by the wave
period with zero up-crossing. Fig.7 shows the relation
between the Ns values and the surf similarity parameter ξz
where the damage ratio is 0% or 2%. The filter layer is
composed of gravels. In our tests, ξz was in the range of
3 to 5.
      In case of 0% of the damage ratio, even though the data
is scattered, the Ns value has a tendency to decrease with
the increase of ξz. 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 ξz and Ns is shown in Fig.8. From this
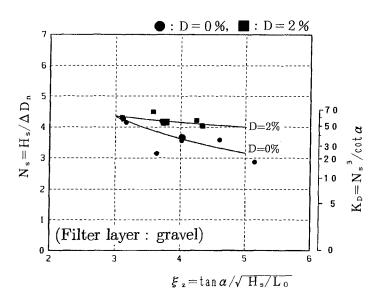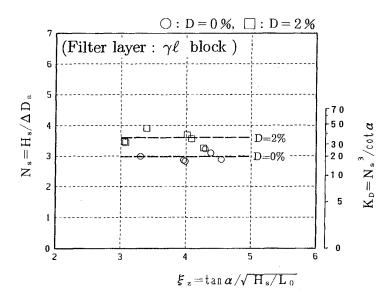figure, the influence of the wave period is not found.

$\bullet : D = 0\%, \quad \blacksquare : D = 2\%$

(Filter layer : gravel)

Fig.7   Stability of The ACCROPODE
(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 $\gamma \ell$ 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 $\gamma \ell$ 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 $\gamma \ell$ blocks for the weight of the ACCROPODE units. However such relationship was not recognized since the unevenness 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 ξz was 3 and increases with the increase of ξz. Holtzhausen and Zwamborn (Ref.1) gave caution that the time from start of damage to failure is shorter for steeper slopes.

$$\xi_z = \tan \alpha / \sqrt{H_s/L_0}$$
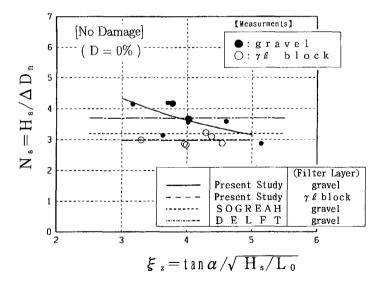
Fig.9-1 Stability of The ACCROPODE by Different
         Investigations (at No Damage)
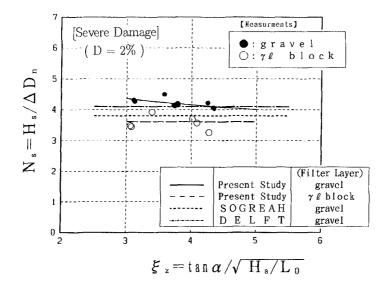
Fig.9-2 Stability of The ACCROPODE by Different
         Investigations (at Severe Damage)

Reflection coefficient

The reflection coefficient KR , 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
KT , 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 trans-
mission 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 hc/Hs , where hc
is the crest height above the sea level. In this figure,
the typical curve of the transmission coefficient can be
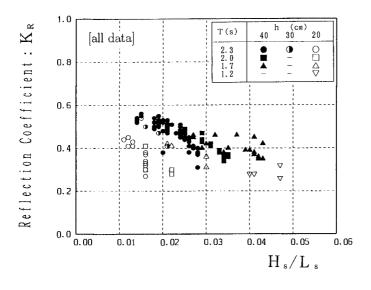drawn.

Fig.10   Reflection Coefficient
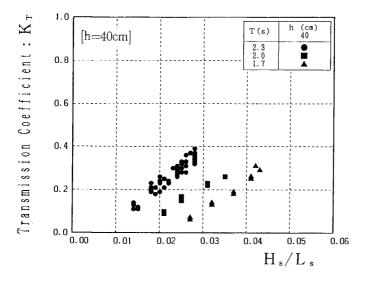   vs. Wave Steepness

Fig.11   Wave Transmission Coefficient
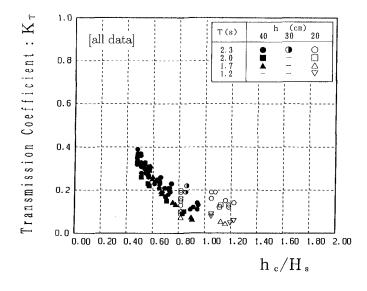   vs. Wave Steepness

Fig.12   Wave Transmission Coefficient
          vs. Relative Crest Height (hc/Hs)

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 $\gamma \ell$ 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 $\gamma \ell$ blocks in the filter
layer, the failure mode, the randomness of installed blocks
especially below the sea level, and the unpreceded
experience in Japan.
     The KD value could be increased even up to 15.

Table 2   Design Conditions

Water depth at the structure	2.0 m – 6.0 m	6.0 m – 8.0 m	8.0 m – 10.0 m
Slope angle (cot α)	1.25	1.33	1.33
Design significant wave height	4.9 m	5.9 m	6.7 m
ACCROPODE's weight (by Hudson formula)	10.8 t	18.9 t	27.6 t
ACCROPODE's weight (applied)	14.5 t	20.7 t	27.6 t

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

Maximum Wave

Date	Wave Height (m)	Wave Period (sec)	Cause
1991. 2.16.	9.41	12.3	Low Pressure
1993.11.14.	8.36	9.5	Low Pressure
1993. 8.27.	7.60	12.5	Typhoon
1993. 3. 8.	7.39	11.0	Low Pressure
1994. 9.19.	7.05	12.5	Typhoon

Significant Wave

Date	Wave Height (m)	Wave Period (sec)	Cause
1991. 2.17.	5.52	15.8	Low Pressure
1993.11.14.	5.00	10.4	Low Pressure
1993. 3. 8.	4.94	10.8	Low Pressure
1993. 8.27.	4.61	10.9	Typhoon
1992.10.21.	4.11	10.2	Low Pressure

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 occured 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 $\gamma \ell$ block's filter,

it was 20.
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.

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