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Development of New Types of Breakwaters

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Abstract:

The increase of waterfront development projects has intensified the demand for breakwater constructions under severer natural conditions than ever and has created such new technological requirements as seaside amenity and harmony with the surrounding environment. In the past several years, Nippon Steel Corporation has engaged in the development of new types of breakwaters. As a result, an H-shaped slit plate jacket-type breakwater, called the CALMOS (for calm offshore structure), was developed jointly with the Public Works Research Institute of the Ministry of Construction and Toda Construction Company. This breakwater was installed as a detached breakwater on the Kanbara Beach under the direct jurisdiction of the Ministry of Construction. Further, a sloped plate-type breakwater, called the PSR (for pile-supported reef), was built at the west wharf of Nippon Steel's Kimitsu Works. Nippon Steel also started joint research with the Port and Harbor Research Institute of the Ministry of Transport, aiming at the development of a full-fledged breakwater for protection against high ocean waves.

1. Introduction

Recent years have seen a growing trend toward waterfront and offshore development for effective utilization of coastal regions. Government ministries and agencies have formulated various plans of their own in this line, including the "Marine Multi Zone (MMZ)" plan by the Ministry of Construction, the offshore man-made island plan by the Ministry of Transport, and the "marinnovation" plan by the Fisheries Agency. These programs call for intensified disaster prevention for harbor facilities, fishing port facilities and shore protection facilities as well as enhanced compatibility of such facilities with their environment in terms of recreation space, landscape and seaside amenity. Various organizations have been carrying out active work on the research and development of new types of breakwaters to meet these technological requirements.

Against this background, Nippon Steel has for years engaged in the development of new breakwaters capable of overcoming harsh natural conditions, such as great water depths, high waves and soft grounds, while caring for landscape, harmony with surroundings, and environmental protection. One example is a pile-supported structure fit with wave dissipating plates for added wave quelling capability. Where waves are too rough to withstand with piles alone, a jacket structure with piles reinforced with steel pipes is used. Jacket structures can be constructed easily because piles are driven using the jacket as a template, and can be installed quickly because they are prefabricated. Many jacket-type structures have been installed as offshore oil drilling platforms in various parts of the world. They boast abundant construction records with excellent service reliability. Nippon Steel has built many of them mainly as offshore oil drilling platforms,

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and recently, constructed a jacket-type embankment for the Kawasaki artificial island of the Trans-Tokyo Bay Highway.

The pile-supported jacket structure offers the following advantages when used in the construction of breakwaters:

(1) Breakwaters can be constructed with relative ease and economy in deep-water areas, high-wave regions, soft grounds, steep shores, and other places where conventional gravity-type structures are difficult to build.

(2) The marine site construction period can be shortened by prefabrication.

Nippon Steel has pushed on with the development of three types of breakwaters to suit specific purposes of use and natural conditions: 1) the calm offshore structure (CALMOS); 2) the pile-supported reef (PSR); and 3) sloped-top pile-type breakwater. Introduced below are the development details, structural outline, and application examples of these new types of breakwaters.

2. Development of CALMOS

2.1 MMZ conception and offshore wave and current control structures

Coastal regions open to oceans are generally exposed to severe oceanographic conditions like waves and are susceptible to erosion. This has been a major limiting factor in the utilization of such coastal areas. With the shortage of land for the construction of seaside amenity spaces and recreational facilities in response to the increasing demand for marine recreation, there has been increasing necessity for creating new marine and offshore spaces in coastal regions.

The Marine Multi Zone (MMZ) is a conception proposed by the Ministry of Construction against this background. It is a train of plans aiming at comprehensive development and utilization of coastal regions through the creation of wide and calm sea areas with offshore wave and current control structures in place of conventional block-type detached breakwaters, and through the formation of waterfront spaces by curing sands into artificial beaches. Since 1986, the Public Works Research Institute of the Ministry of Construction, and 15 private companies have jointly developed various types of offshore wave and current control structures. The clam offshore structure (CALMOS) is one example, which is an outcome of joint development efforts by Nippon Steel, Toda Construction, and the Public Works Research Institute, Ministry of Construction.

2.2 Outline of CALMOS

The CALMOS is schematically illustrated in **Fig. 1**. Vertical and horizontal permeable wave dissipating plates are assembled into H form and are integrated with a steel-framed reinforced concrete (SRC) top structure and a steel jacket. Besides the above-mentioned structural and constructional characteristics, the CALMOS has the following hydraulic characteristics:

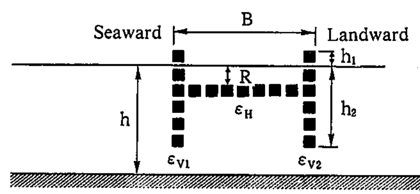
(1) It has wave dissipating function similar to that of the block-type detached breakwater and has the function of a levee on the beach behind.

(2) It has openings provided below the vertical wave dissipating plates for seawater exchange through them.

(3) It has small wave force acting on the permeable wave dissipating plates and can be very economically constructed under severe construction conditions, such as great wave height and water depth.

(4) It needs no maintenance over its long working life.

The CALMOS dissipates the arriving waves by reflecting them at its vertical and horizontal wave dissipating plates and causing wave energy loss through turbulence while passing through the slits in the wave dissipating plates. **Fig. 2** gives the structural data of the CALMOS. The relations between these structural data and



Structural data	Symbol
Breakwater body width	B
Vertical plate draft ratio	h_2
Vertical plate top height	h_1
Horizontal plate draft ratio	R
Opening ratio	
Vertical	$\varepsilon_{V1}, \varepsilon_{V2}$
Horizontal	ε_H

Fig. 2 Structural data of slit-type CALMOS (H-shaped, slit plate, jacket type)

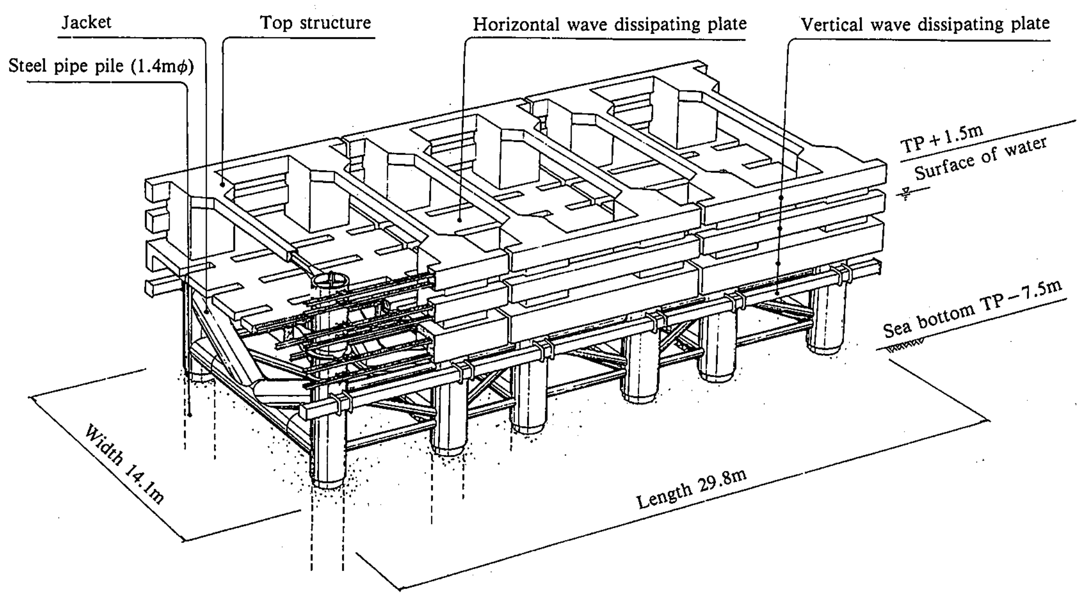


Fig. 1 Schematic illustration of CALMOS

wave conditions and the wave dissipating characteristics expressed by the transmission coefficient K_T and the reflection coefficient K_R are confirmed by various hydraulic model experiments at the Public Works Research Institute.

Fig. 3 shows the relationship between the transmission coefficient K_T and the ratio of the breakwater body width B to the wavelength L that has a large effect on the wave dissipating characteristics of the CALMOS. As evident from the figure, the transmission coefficient K_T decreases or the wave dissipating function increases with increasing breakwater body width. Assuming the construction of the CALMOS in the wave breaker zone where it is subject to impact wave force, hydraulic model experiments are under way for measuring the wave force in the clapotis region to the wave breaker region. **Photo 1** shows a breaking wave force experiment on a sea bottom with 1/10 slope.

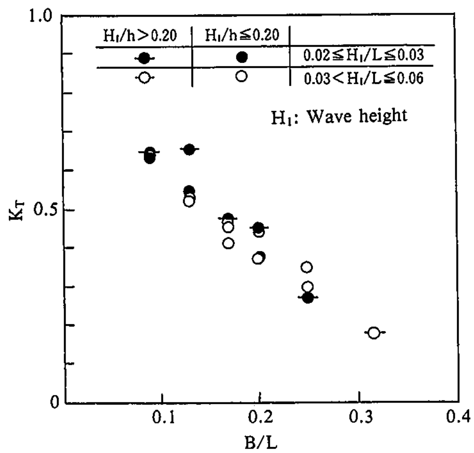


Fig. 3 Relationship between breakwater body width-to-wavelength ratio (B/L) and transmission coefficient K_T

2.3 Example of application on Kanbara Beach, Shizuoka Prefecture

2.3.1 Description of Kanbara Beach

The Kanbara Beach is the shore of Kanbara Town, situated to the west of the Fuji River mouth and is known as a production center of spotted shrimp. The townspeople crowd a narrow and flat belt on the Suruga Bay. The Tokaido railway line, national highway route No. 1, and other principal transportation arteries run in parallel with the coastal levee of the Kanbara Beach. The beach is characterized by a steeply sloped sea bed

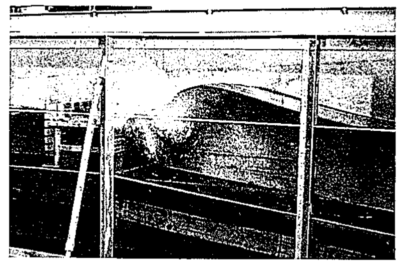


Photo 1 Wave breaking force experiment of CALMOS

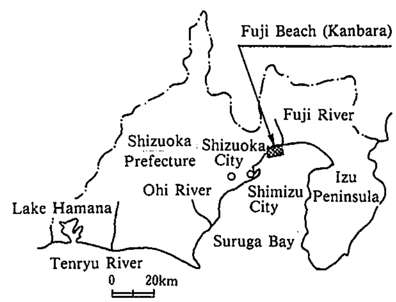


Fig. 4 Construction site of CALMOS

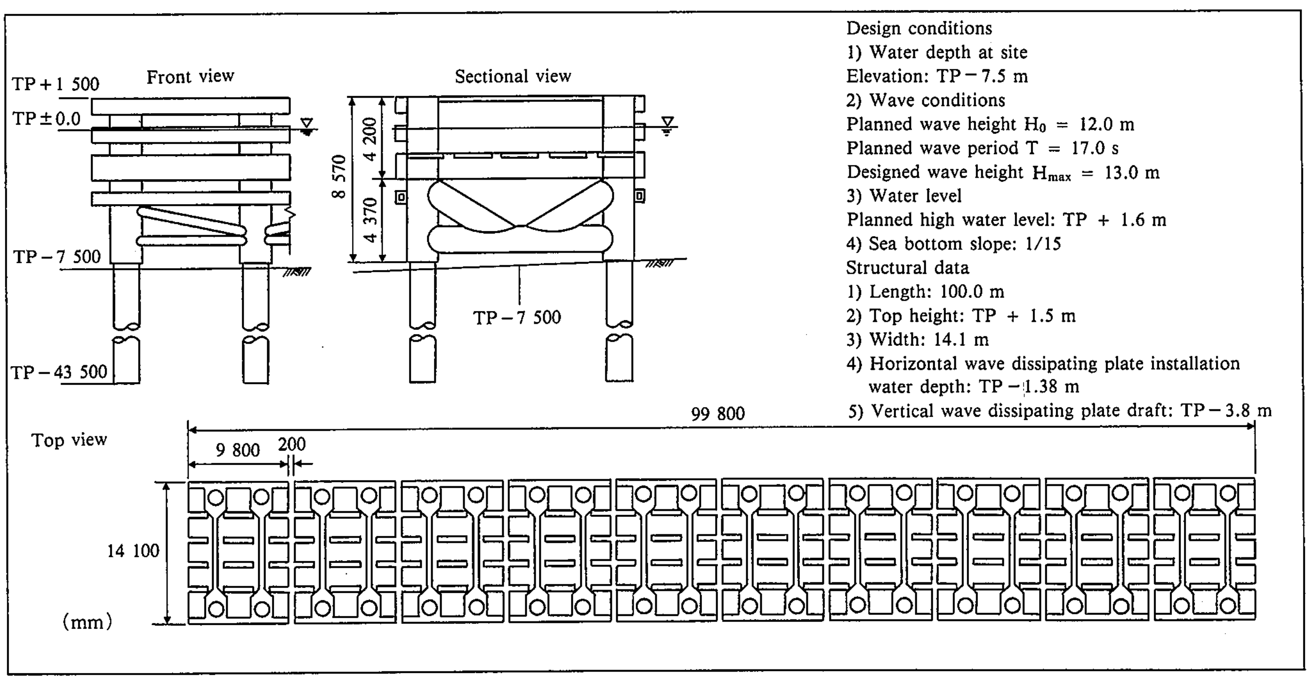


Fig. 5 Design conditions and structural data of CALMOS

and is often plagued with disasters arising from high waves. In fiscal 1967, the Ministry of Construction started work on improving the coastal levee and other facilities. In 1992, the CALMOS was adopted as a detached breakwater to be built 150 m from the shoreline as part of the project. The construction site is as shown in **Fig. 4**.

2.3.2 Design conditions and method

The design conditions and structural data are shown in **Fig. 5**. The structural data of the CALMOS were determined from past research results to be a wave dissipating performance of $K_T \leq 0.6$ and $K_R \leq 0.5$ against a wave period of 10 s and significant height of 3.5 m for the average height of the five largest waves to occur in a year. The sections of the jacket and the SRC top structure were determined by structural computation for storm and earthquake forces using two-dimensional and three-dimensional framework models while considering the nonlinearity of the ground at the construction site. It was confirmed, that the jacket panel points have sufficiently high fatigue strength against waves that would be expected to repeatedly act on the CALMOS over the design service life of 50 years.

2.3.3 Fabrication and construction

The jacket was fabricated at the Wakamatsu Fabrication Center of Nippon Steel, and the SRC top structure was built at a yard next to the Shimizu Port. The fabricated jacket and SRC top structure were then transported by sea barge to the construction site. Considering the seasonal rate of effective working days at sea, the construction work was executed at the site in February and March, 1993. As shown in **Fig. 6**, the CALMOS was built in the order of 1) driving of temporary piles, 2) erection of jacket, 3) driving of steel pipe piles, 4) erection of SRC top structure, and 5) grouting. **Photo 2** shows the jacket fabrication at the Wakamatsu Fabrication Center, and **Photo 3** the jacket erection at the site.

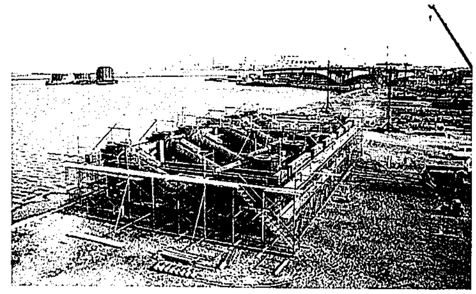


Photo 2 Jacket fabrication of CALMOS

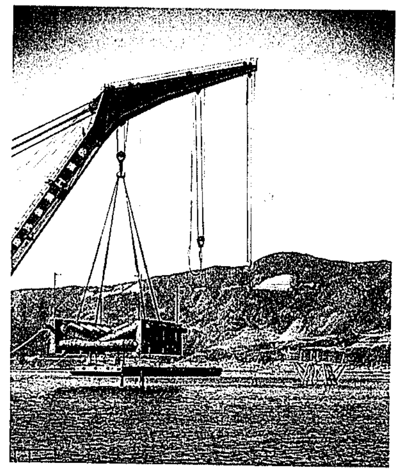


Photo 3 Jacket erection of CALMOS

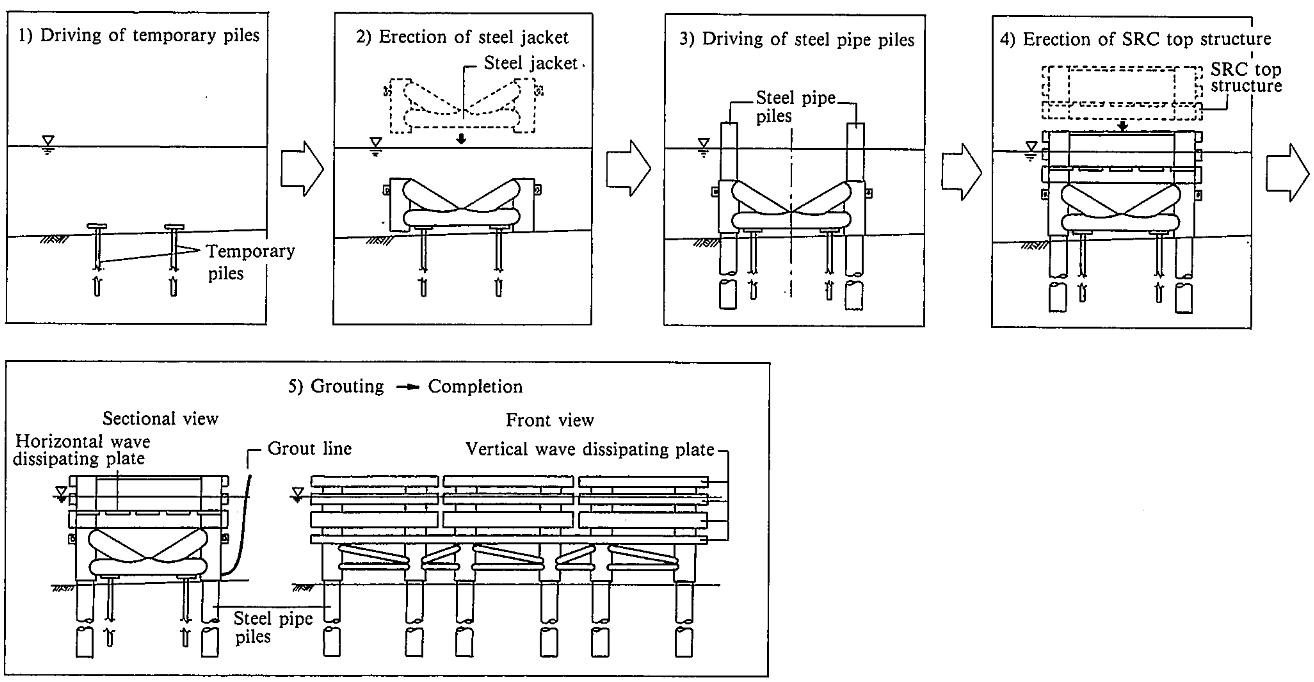


Fig. 6 Flow diagram of CALMOS construction

3. Development of PSR

3.1 Details of development

In recent years, the construction of fishing ports and the expansion of finishing grounds in deep-water and soft-ground sea areas have been projected, which call for wave dissipating breakwaters that can be constructed under severe natural conditions while securing water quality. Such breakwaters are required further to ensure harmony with the environment, assuring beautiful landscape and allowing marine recreation. To meet these demands, various new types of breakwaters are being developed in various quarters.

Nippon Steel carried forward the development of a sloped-plate breakwater or pile-supported reef (PSR) featuring water passage and low reflection characteristics. It can be constructed in deep-water and soft-ground sea areas. In this PSR development, guidance from the Department of Civil Engineering, University of Tokyo, was sought for the clarification of hydraulic characteristics.

The PSR is schematically illustrated in **Fig. 7**. A flat plate is secured to steel pipe piles or a jacket structure near the water surface with a mild angle of 10 to 30° to the horizontal. An offshore wave approaching a natural beach finds it increasingly difficult to retain its form with decreasing water depth and eventually breaks. This breaking phenomenon consumes the energy of the wave and sharply reduces the wave height. The PSR makes use of the wave breaking phenomenon. It provides a wave dissipating effect by reflecting and breaking incoming waves with the sloped plate that plays the role of an artificial sea bed.

Characteristics of the PSR may be summarized as follows:

(1) Since the PSR can accomplish a reflection coefficient much smaller than that of conventional breakwaters by wave energy dissipation through wave breaking, it can minimize the effect on small ships.

(2) Since the horizontal wave force acting on the sloped plate is small, the PSR can more economically work than conventional breakwaters in deep-water and soft-ground sea areas representing severe construction conditions.

(3) The PSR does not obstruct seawater exchange and is effective in securing seawater quality.

(4) A catwalk and other devices can be easily installed to allow the PSR to be utilized for multiple purposes.

(5) The angle, draft, and top height of the PSR can be judiciously combined to provide the necessary transmission coefficient and reflection coefficient.

The PSR may be applied as a breakwater, detached breakwater, inner breakwater, or wave dissipating structure in front of a revetment. As the PSR is particularly effective in dissipating waves with a high water depth-to-wavelength ratio, it can serve as an economical breakwater with water passage and low-reflection characteristics in deep-water areas within harbors. The PSR is scheduled for use as one of breakwaters in the Yobihito Port of Abashiri, Hokkaido.

Construction of the PSR at the west wharf of Nippon Steel's Kimitsu Works is described as an example of PSR application in which its low-refection characteristic is best utilized.

3.2 PSR construction at west wharf of Kimitsu Works

In December 1990, the PSR was built for the first time as a breakwater at the west wharf of the Kimitsu Works for the purpose of reducing reflected waves in the waterway of the adjacent Koito River fishing port in Kimitsu, Chiba Prefecture. The effect of the PSR in reducing reflected waves in the actual sea was confirmed by wave observation at the site.

3.2.1 Construction details and site

As shown in **Fig. 8**, the Kimitsu waterway is sandwiched between the west revetment of the Kimitsu Works and the Futtsu reclaimed land. Reflected waves from both sides tend to increase the wave height, depending on seasons. The area in front of the west revetment was therefore hazardous to the navigation of fishing boats entering and leaving the Koito River fishing port located deep in the Kimitsu waterway. After consultation with the Chiba Prefecture, Nippon Steel decided to construct 31 PSR units, each measuring about 12 m long for a total length of 362 m as a breakwater in front of the west revetment.

3.2.2 Wave conditions and structural data

Safe navigation of fishing boats required the dissipation of waves of 3 s in period and about 1 m in height at the reflection coefficient of 0.3 or less. The structural data listed in **Table 1** were selected on the basis of past research results and results of hydraulic model experiments conducted under the site conditions.

3.2.3 Fabrication and site construction

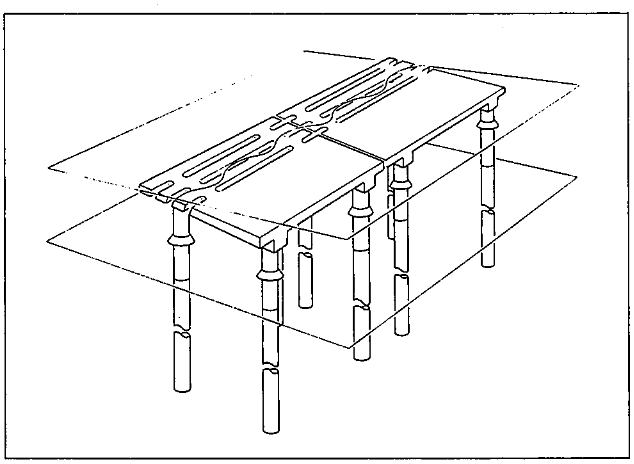


Fig. 7 Schematic illustration of PSR

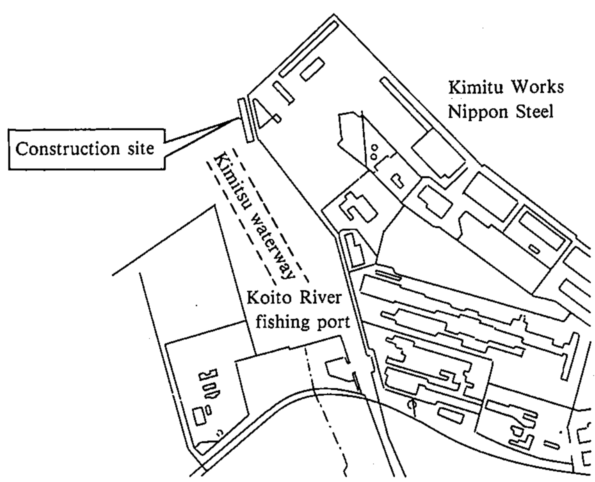
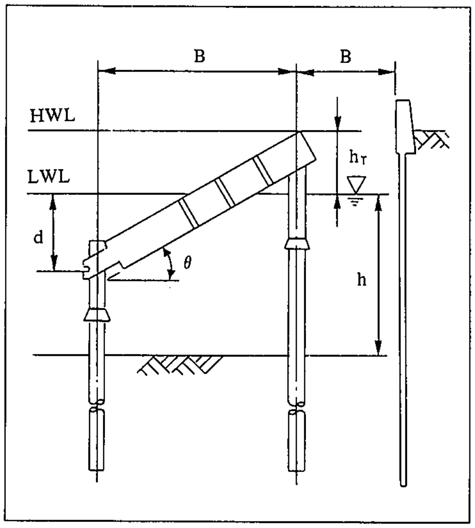


Fig. 8 Diagram of PSR construction site

Table 1 Data of PSR construction at west revetment of Kimitsu Works

Data	Symbol	Set value
Water depth	h	AP−5.0 to −2.0 m
Water level High water level Low water level	 HWL LWL	 AP + 2.0 m AP ± 0 m
Distance from rear revetment	B'	4.0 m
Angle of sloped plate	θ	20°
Bottom of sloped plate	d	AP−1.5 m
Top of sloped plate	h_T	AP+2.0 m
Width of a slope plate	B	10.2 m



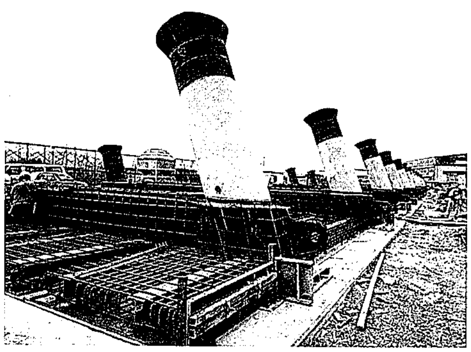


Photo 4 Fabrication of PSR

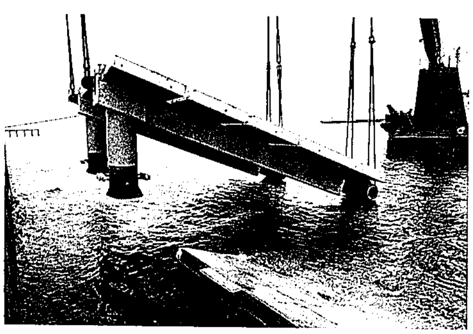


Photo 5 Installation of PSR

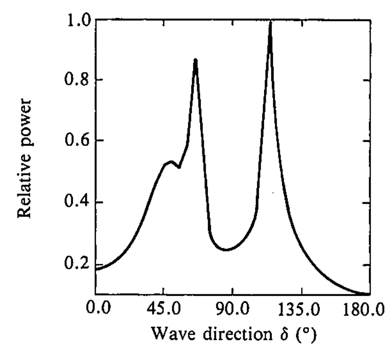
This project involved installing a sloped plate on pre-driven steel pipe piles in due consideration of wave height and water depth at the site. The sloped plate was a steel-framed reinforced concrete (SRC) structure having H-beams covered with reinforced concrete. The SRC sloped plate measures 10.2 m wide, 11.6 m long and 0.35 m thick, weighs 130 tons, has 20 cm wide slits cut for the purpose of wave force reduction, and is supported by four steel pipe piles. The steel frame fabrication, reinforcement placement, and concrete casting of the SRC sloped plates were all performed at the Wakamatsu Fabrication Center. **Photo 4** shows the fabrication of the PSR.

Each SRC sloped plate was towed to the site, lifted by a floating crane, and installed on 700 mm diameter steel pipe piles driven beforehand. **Photo 5** shows the PSR installation. The sloped plate and piles were joined by grouting poured into the gap between each leg and pile to integrate the sloped plate with the steel pipe piles. The piles were protected against corrosion by heavy coating for the splash zone and cathodic protection for the submerged and subsoil zones.

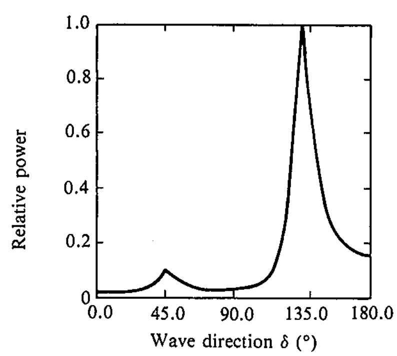
Extensive prefabrication made it possible to complete the construction of the 360 m long PSR breakwater in a mere 3 months.

3.2.4 Wave observation at site

Waves at the site were observed to verify the validity of the PSR in reducing reflected waves in an actual sea. Three wave gage arrays were installed at the center of the PSR breakwater and used to observe waves at the site for about 1 month each before and after the PSR installation. The observed wave data were analyzed by the modified maximum likelihood method developed by Isobe et al., and directional spectra were computed from the analyzed data. The effect of the PSR breakwater was confirmed by comparing the directional spectra before and after the PSR



(a) Before PSR installation



(b) After PSR installation

Fig. 9 Directional spectra of waves before and after PSR installation

installation.

Fig. 9 shows the directional spectra obtained from the wave data measured in stormy weather before and after the PSR installation. The relative power normalized by the power of incident waves is shown in each diagram. Given the line of breakwater alignment, incident waves range from 90° to 180° in direction, and reflected waves are considered to be present in the direction range of 0° to 90°. As evident from the directional spectrum before the PSR installation shown in **Fig. 9(a)**, the incident wave energy peaks in the wave direction of 115°. The corresponding reflected wave component is present in the wave direction of 65°. The energy of reflected waves is as much as 88 % of that of incident waves. This is nearly a total reflection. In the directional spectrum after the PSR installation shown in **Fig. 9(b)**, the energy of incident waves peaks in the wave direction of 135°. The energy of corresponding reflected waves is a mere 9.7 % of that of incident waves. This energy value is convertible into a reflection coefficient of 0.27 and confirms the effectiveness of the PSR breakwater in dissipating waves in the actual sea environment.

4. Development of Sloped-Top Pile-Type Breakwater

4.1 History of development

In recent years, seaports have been expanding outward. As port construction sites shift to outlying areas of harbors, breakwaters must be constructed in sea areas under severer natural conditions with heavier waves and softer shore grounds. Composite breakwaters with caissons or blocks piled on a rubble mound have traditionally been the mainstay of breakwaters. Depending on site conditions, they require soil improvement over a wide area and are not economical. Furthermore, the progress of waterfront development is accompanied by social requirements for conserving the harbor environment, preventing the river-mouth shoaling of the waterway, ensuring the navigational safety of small boats, and improving the harbor in emergency, and so forth. Breakwater facilities call for increasing technological needs for water passage, low wave reflection, and massive and rapid construction as well as basic functions.

Given these conditions, Nippon Steel started in 1992 a two-year joint study with the Port and Harbor Research Institute of the Ministry of Transport, toward the development of a sloped-top pile-type breakwater that could be economically built in deep-water, high-wave, and soft-ground sea areas and provide good water passage and rapid construction.

The above-said breakwater is schematically illustrated in **Fig. 10**. A concrete slab is attached to the front of a steel jacket as the figure shows. It resembles a curtain wall-type breakwater comprising a curtain of concrete slabs supported by steel pipe piles. The curtain wall-type breakwater has been adopted mainly in small-wave and calm sea areas such as bays and inlets, because large-scale soil improvement is not required in soft-ground sea areas and because material and construction costs are low. Its construction in a high-wave sea area with oceanic swell, however, calls for solving several problems. That is to say, it does not have sufficient load-carrying capacity because it is predominantly constructed of piles and the joints between the piles and wave dissipating plates are not strong enough against high waves. The top height and curtain wall depth must be increased to ensure calmness against higher waves of longer period, resulting in less economical construction.

With the sloped-top pile-type breakwater, the piles are reinforced by a jacket structure. Necessary load-bearing capacity is obtained through the development of wave dissipating plate-jacket joints strong enough against high waves. The following water permeation as well as cost saving measures are also incorporated to reduce the transmitted wave height (transmission coefficient $K_T < 0.2$ to 0.6) for offshore waves containing swell and provide the functions required as a disaster prevention facility:

(1) Economy factor

A sloped plate is provided near the water surface to reduce the horizontal wave force and increase economy. For a wave and

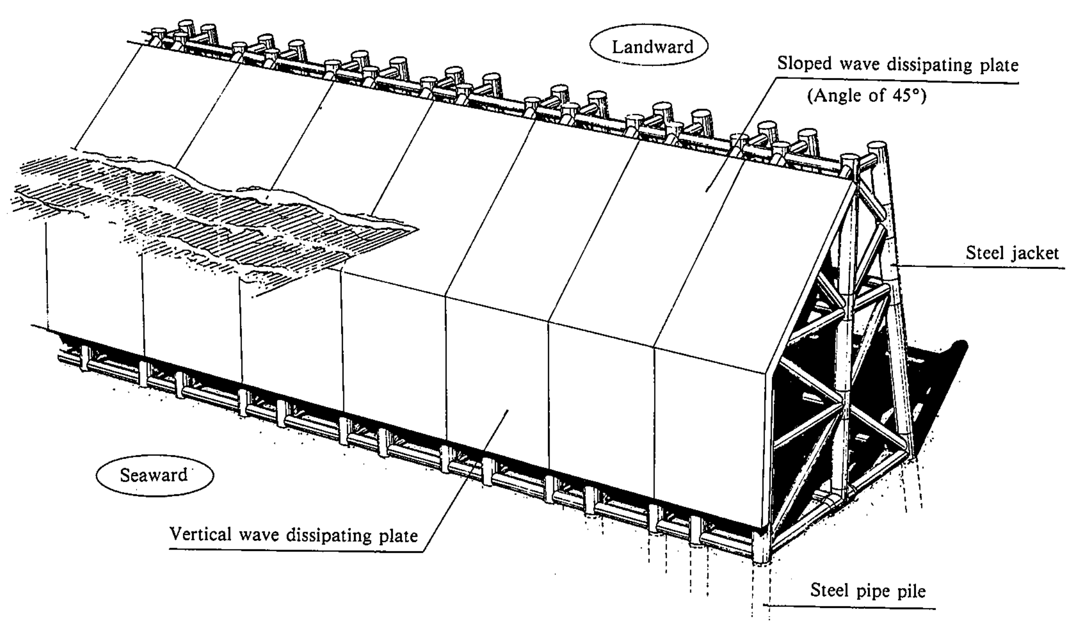


Fig. 10 Schematic illustration of sloped-top pile-type breakwater

current control structure that need not provide high calmness in the protected sea area, the top height can be lowered to reduce the wave force with economy.

(2) Water permeability

Openings are provided near the sea bottom to ensure clean water in the harbor and secure the environment within the harbor.

Hydraulic model experiments were conducted in a large wave flume of the Maritime Structures Laboratory, Hydraulic Engineering Division, Port and Harbor Research Institute, in order to determine the effects of the structural details of wave dissipating plates on the wave dissipation and wave force characteristics of the sloped-top pile-type breakwater. One of such experiments is shown in **Photo 6**. The authors plan to clarify the hydraulic characteristics of the sloped-top pile-type breakwater and to study the strength of the joints between the wave dissipating plate and jacket structure.

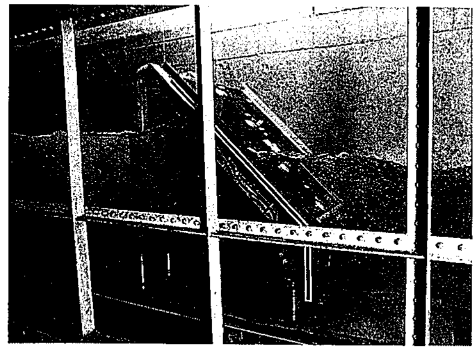


Photo 6 Hydraulic model experiment of sloped-top pile type breakwater

5. Conclusions

Nippon Steel has achieved solid results in the realization of breakwaters to assure economy, rapid construction, and water passage under such harsh conditions as soft-ground, deep-water, high-waves and steep-slope sea or beach areas, utilizing the offshore structure technology it possesses. The authors intend to continue on their development work with the aim of enhancing the effective utilization of coastal regions.