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Synopsis :
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This paper describes the civil engineering aspects of the steel pipe pile foundation used in this construction project.

1 Introduction

After an international tender, the Engineering Division of Kawasaki Steel Corporation was awarded a contract by Taiwan Power Company in April 1981 to construct an offshore berth facility for unloading coal. It was decided to use approximately 4 400 t of large-diameter heavy-wall UOE steel pipe (1.5 m in diameter) made by the company for the foundation piles of the offshore berth facility consisting of a platform and an approach trestle.

This paper presents some technical features concerning the use of the steel pipe piles for the construction of this offshore berth facility about 1 km off the coast.

Taiwan Power Company is constructing a steam power plant in the Hsinta district located about 30 km north of Kaohsiung. Two 500 000 kW generators have already been constructed as the first phase of the project and they are now operating. This power plant will require as much as 3 000 000 t/year of coal during the first phase of its operation program and 12 000 000 t of coal in the final fourth phase in order to provide a capacity of 4 000 000 kW. Taiwan Power Company planned to construct in Kaohsiung a coal center capable of handling coal from a 100 000 DWT vessel during the first phase with secondary transportation from there to Hsinta using 10 000 DWT barges. It was therefore, necessary to consruct harbor facilities to accommodate a 100 000 DWT vessel, load 10 000 DWT barges in Kaohsiung and receive 10 000 DWT barges in Hsinta. This paper relates to the construction of the offshore berth facility for unloading imported coal for the Hsinta Steam Power Plant from 10 000 DWT barges.

A total of 98 steel pipe piles, 1 500 mm in outside diameter, 25 and 36 mm in wall thickness and 33.0 to 55.0 m in length, were planned for this construction work. In driving fabricated steel pipe piles for offshore structures, economy and the shortest possible construction period are vital to success; that is, to minimize marine welding and make best use of piles in full length as much as the capacity of the construction equipment (pile driving barges and hammers) permits. In cases where the period of construction is limited to one season as in this construction work, it was absolutely necessary to avoid welding at sea which may be affected by waves and wind because various technical difficulties are usually encountered.

It was, therefore, planned to transport pipe sections (18 m maximum in length) to the construction site, weld and join them into piles of the desired length. Full measures of technical care were taken so that all pipe piles thus fabricated would pass X-ray examination.

The second technical difficulty related to the driving of the field-fabricated large-diameter steel pipe piles (72 t maximum) was a driving of piles at high accuracy using

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a large pile-driving ship. A high driving accuracy was particularly required for driving batter piles (18°26′). Furthermore, it was necessary to ensure depths of penetration of more than 5 m in fine sand layers with standard penetration test *N*-values of more than 40 and vertical bearing capacity of 1 470 t.

In addition to the above-mentioned items, this construction work included concrete placement in open water, installation of navigation aids, corrosion protection system, etc. Due to space limitations for this technical report, however, these items are omitted from the discussion and only the three technical points mentioned above are presented.

2 Scope of Work

2.1 Size of Facilities

This offshore berth facility for unloading coal is composed of a 910 m long approach trestle, a concrete plat-

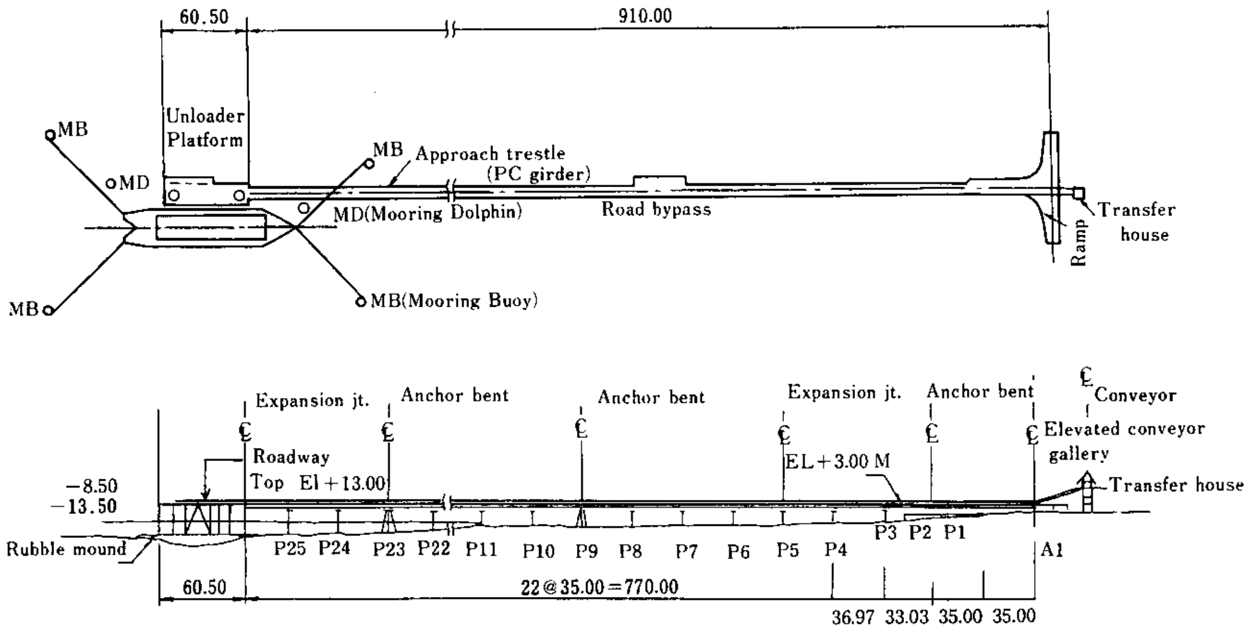

Fig. 1 Layout plan of offshore facility (m)

Table 1 Outline of facility

Facility	General description	Super-structure	Foundation
Trestle	910 m (length)	P.C. girder (T-type, 35 m span, 84 pcs)	Steel pipe pile (φ1 500mm × *t* 25 mm × *l* 41.5~55 m 57 pile; 〃 ×36 〃 × 〃; 700 mm × 19 mm × 41.5 10 pile)
Offshore platform	19.5 m × 60.5 m (size) Unloader : 2 sets, 1 100t/h	RC (cast in place)	Steel pipe pile (φ 1 500 mm × *t* 25 mm × *l* 44~54.5 m 32 pile)
Breasting dolphin and Mooring dolphin	10 000 DWT (Berthing Vessel) (122.3 mL × 25 mW × 7.8 mD; Loaded draft=6.0 m)	Fabricated steel, rubber fender, bollard, quick release hook with capstan	Steel pipe pile (φ1 500 mm × *t* 25 mm × (*l* 41.5~55 m; 35 〃), 8 pile
Navigation aids	4sets (100 t) Mooring buoy 2sets Lighted buoy 2sets Light beacon 1sets Fog horn 2sets Docking sonar with display board		

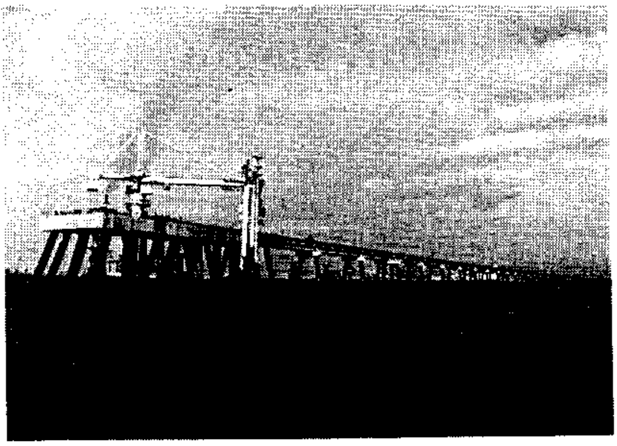

Photo 1 General view of coal unloading facility

Table 2 Major construction items and quantities of work

Items	Quantities
1. Steel pipe piles	
(1) Fabrication	○ ϕ1 500 4 210 t, ϕ700-135 t(Total weight: 4 345 t, Number of pile joints: 201 joints)
(2) Pile driving	○ ϕ1 500-98 piles 4 428.2 m(total length) ϕ700-10 piles -415.0 m(total length)
2. Concrete	○ Total concrete volume : 7 715 m^3 Pile cap concrete : 1 499 m^3 Platform : 2 419 m^3 Expansion concrete : 788 m^3 PC Girder (84 pcs) : 2 190 m^3 Others : 819 m^3
3. Reinforcing bars	○ 957 t
4. Prestressing strands wire	○ 105.4 t
5. Paint for steel pipe piles	○ 4 682 m^2 (Tar epoxy coat)
6. Cathodic protection	○ 16 998 m^2 (Aluminum alloy anode)
7. Tape wrapping and FRP cover	○ 1 378 m^2 (Denso tape and F.R.P. cover)

form for the unloader foundation, a 10 000 DWT barge berthing and mooring facility and navigation aids.

Figure 1 shows the layout plan of this offshore berth facility. **Photo 1** shows the general view of the facility after completion. **Table 1 and 2** give an outline of the facility and the quantities of work required for the construction.

2.2 Natural Conditions

(1) Waves and swells

The waves at the site are influenced by monsoons blowing from north-northeast due to high pressure over the Continent between October and March and winds blowing from southwest and west due to tropical cyclones during the months from June to August. Between April and May and again in September the direction of wind changes and the climate is relatively mild. Although winds blowing from north-northwest have no great effect on waves, winds from southwest and west have long fetches, and waves often develop into swells. Although the waves caused by ordinary winds are 1 m or less in height, waves (1/3-significant waves) under the influence of typhoons are about 2 to 3 m high.

(2) Tides

Table 3 gives the tidal range based on past observation data obtained near the site. The range of tide for one day is small.

Table 3 Tidal Range

Highest high water level (HHWL)	+2.2 m
High water level (HWL)	+0.71 m
Mean high water level (MHWL)	+0.46 m
Mean water level (MWL)	+0.22 m
Mean low water level (MLWL)	−0.02 m
Lowest low water level (LLWL)	−0.53 m

(3) Tidal currents

The past observation data indicate that tidal currents near the site have velocities of less than 60 cm/s at a depth of about 7 m and velocities of less than 70 cm/s at a depth of about 21 m. Ordinary velocities range between 0 and 30 cm/s. According to the observation data obtained near the platform (water depth: 8 m) during the sea berth construction in 1981 and 1982, however, strong tidal currents of about 1 m/s were observed to flow from south and north at midtide every day.

(4) Soil

Figure 2 shows the standard boring log of the site. The sub soil is generally composed of fine sand layers (most grain diameters are 0.1 mm and even relatively coarse grains have maximum diameters of 3 to 6 mm). The N-value of the intermediate sand layer is 30 to 35 and it was relatively difficult for a pile to penetrate into more than 15 m of this layer by using a D-80 class hammer. Although there is no clear interface with the bearing layer, the fifth layer that provides dense and fine silty sand was regarded in the design as the bearing layer. It was almost impossible for the pile to penetrate into the fifth layer even with an air hammer of MRB-2000 class (amount of final penetration per blow: less than 3 mm). It was assumed that the pile bearing capacity is generally provided more by the skin friction of the intermediate layers than by the point-bearing resistance of the

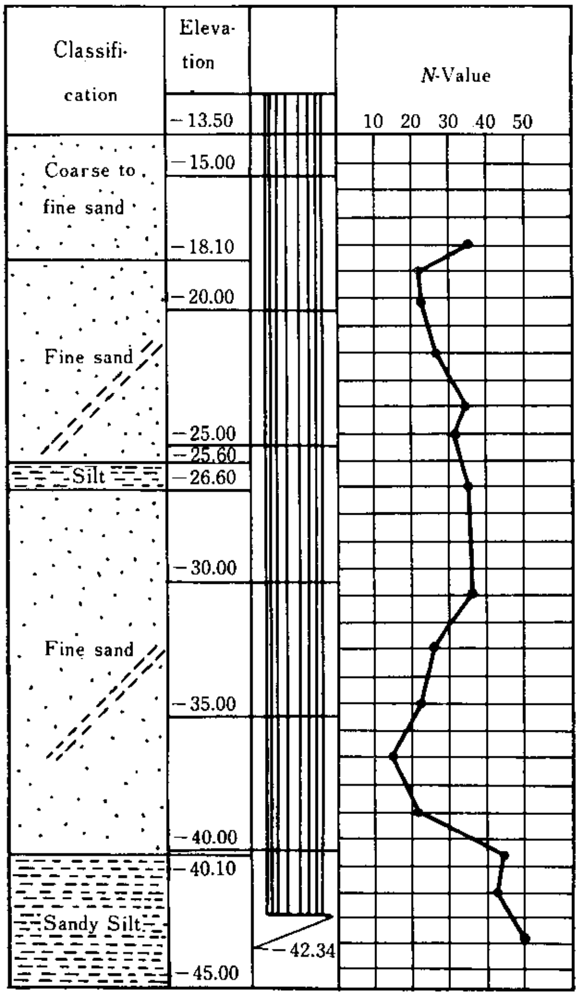

Fig. 2 Soil profile

lower layer.

2.3 Progress of Work

The construction work was started in April 1981. The progress of work for the major items is described below:

(1) Preparatory work
The construction of the temporary sheet pile wharf for this work was almost completed during the three months between April and June, 1981. The dredging work in front of the wharf, however, continued until about October because of rough sea conditions. The construction of the office and warehouse buildings, electric power and water supply facilities, etc. was almost completed by the end of July 1981.

(2) Steel pipe fabrication
Welding was begun on August 13, 1981, one month after the steel pipe and welding equipment arrived at the project site. The welding of 98 piles with 201 joints was completed on December 31, 1981. The welding performance rate was 0.7 pipe per calendar day.

(3) Steel pile driving
It took a large pile driving vessel about 20 days to sail from Japan to Taiwan (Kaohsiung) because of rough seas resulting from a typhoon. At the port of Kaohsiung, 15 days were spent on mobilization preparations for the pile driving equipment. Pile driving was started on October 1, 1981 and was completed on January 23, 1982. Thus, 115 days were required to drive 98 piles. The pile driving performance rate was 0.85 pile per calendar day.

(4) Concrete work
The pile cap concrete installation was carried out upon completion of the pile driving. It was begun in October, 1981 and in June 1982 the concreting of the platform was completed. Thus, it took a total of eight months to place about 4 000 m^3 of concrete.

(5) P.C. girder installation
The fabrication of prestressed concrete girders was carried out between October 1981 and April 1982 at the project site. The installation of P.C. girders was carried out during the eight months between November 1981 and June 1982. The fabrication performance rate was 0.42 girder per calendar day and the installation performance rate was 0.42 girder per calendar day.

3 Fabrication of Steel Pipe Piles

Steel pipe piles used for this project were as long as 33 to 55 m and it was not considered feasible in terms of transportation method and cost for them to be fabricated in Japan and then transported to the site. Therefore, sections of pipe (11 to 18 m long) were transported to the site and piles were fabricated there by using almost the same shop welding techniques and procedures which would be used in the factory. **Photo 2** shows how the field welding was performed.

Riverjoint-AN was adopted for pipe joint fabrication

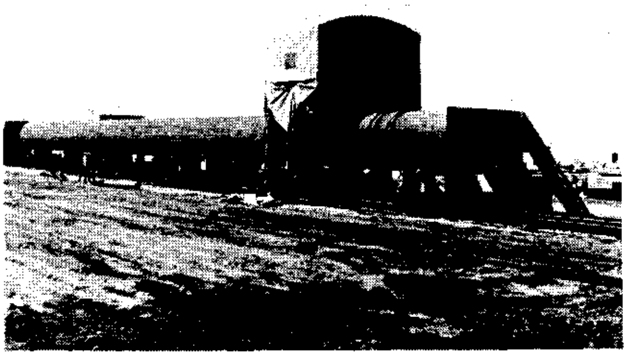

Photo 2 Steel pipe pile welding

and tandem submerged arc welding was carried out. In selecting this welding process, laboratory tests and field tests were conducted beforehand and the validity of this process was confirmed. For details of the welding techniques refer to the literature.[1]

3.1 Performance Rate of Steel Pile Welding

Table 4 gives the performance of welding work. In the initial welding stage, it took more than one day to make one joint because the operators were unaccustomed to the welding operation and equipment, and modifications to procedures had to be made. Afterward the operators became accustomed to the operation to improve efficiency, and it became possible to complete two welded joints per day.

3.2 X-Ray Examination

The quality of the welded joints for the steel pipe piles was inspected using X-ray. X-ray photographs of four spots per joint were taken. This means that a sampling test was conducted on about 25% of the entire weld length.

In this inspection, 93.5% of the joints examined were accepted as Grade 1 in accordance with JIS (Japan Industrial Standards), and others Grade 2. This demonstrates that the quality control over welding of steel pipe piles for this project was excellent.

3.3 Welding Materials Used

The amount of welding materials consumed in the welding of the steel pile joints was as follows:

Welding Wire (KW-50C)	18.9 kg/joint
Flux (KB-120)	24.9 kg/joint
Electrode (KS-76)	2.8 kg/joint

The consumption of welding wires and electrodes was about 1.3 times as large as the estimate.

4 Steel Pile Driving (on the Sea)

There were three main technical problems encountered during the pile driving operations: sea conditions, pile driving accuracy and pile capacity.

Although the project site faces the South China Sea, the sea conditions are relatively calm except during the typhoon season. According to the past data, the frequency of generation of significant waves with a height of less than 1 m is 89% annually. Swells are often produced, however, because of long fetches. Waves are broadly classified into wind waves and swells according to the type of generation. Swells have long wave cycles and high energy and their attenuation is very slow. Since swells have a large impact on pile driving at sea, it was necessary to overcome the swells for this project.

The next problem was pile driving accuracy. It was necessary to drive the trestle piles for a distance of 1 km offshore with a high degree of accuracy. The superstructure was designed with a range of pile driving location and alignment tolerances of 10 to 20 cm, and it was required to meet those tolerances.

The third problem was the pile driving capacity. It was necessary to obtain the required bearing capacity by driving piles (1.5 m in diameter and about 50 m in length) into dense and fine sand layers. For this purpose, piles were positioned using the diesel hammer MH-80B with pile leads and were driven to the final depth using the air hammer MRB-2000. This single-acting air hammer provided a far greater striking power than the diesel hammer.

A 300 t hanging capacity pile-driving barge, a 1 700-PS tug boat and a 35-PS crew boat were used for the pile driving work at sea. **Photo 3** shows how the pile driving was carried out using the large pile driving barge.

Table 4 Rate of pipe joint fabrication

Description			Aug.	Sep.	Oct.	Nov.	Dec.	Total
Working period		Calendar day	19	30	31	30	31	141
		Working day	16	29	20	28	21	114
Accomplishment	Quantity of piles (pcs.)		7	21	20	24	26	98
	Rate of fabrication	pcs. / Calendar day	0.37	0.70	0.65	0.80	0.84	0.70
		pcs. / Working day	0.44	0.72	1.00	0.86	1.24	0.86
	Quantity of Joint (joint)		14	47	40	59	41	201
	Rate of fabrication	joint / Calendar day	0.74	1.57	1.29	1.97	1.32	1.43
		Joint / Working day	0.88	1.62	2.00	2.11	1.95	1.76

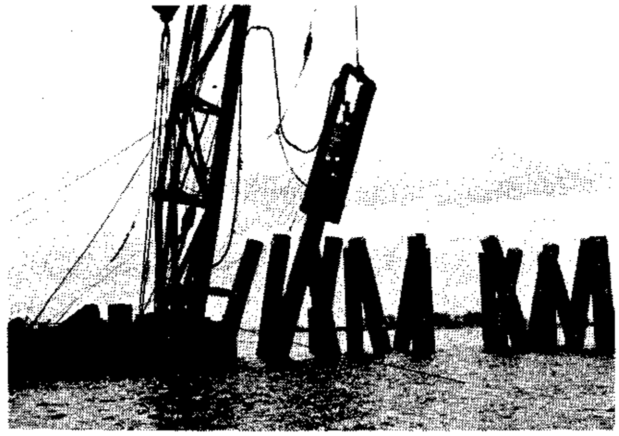

Photo 3 Steel pipe pile driving

4.1 Performance Rate of Pile Driving Work

To increase the pile driving efficiency was one of the most important prerequisites for carrying out the construction of this project as planned. The following items imposed restrictions on the pile driving work:

(1) It was difficult to carry out the pile driving work during the typhoon season from June to September and the monsoon season in December.
(2) Even during periods of the year when the pile driving work was possible, swells were generated in the afternoon and it was difficult to drive the piles.
(3) Because of the topographic and hydrographic restrictions at the pile shipping site, it was difficult to load a flat barge with piles.
(4) Since the driven piles were of large diameter, it was necessary to use both a diesel hammer (MH-80B) and an air hammer (MRB-2000) in order to penetrate to the specified depth. (Pile driving with the diesel hammer was stopped when the amount of penetration per blow became less than 3 mm or the depth of penetration became more than 15 m.)

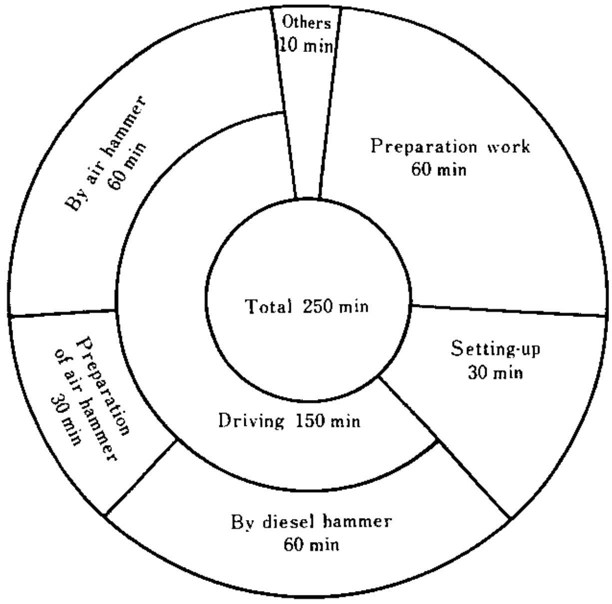

Fig. 3 Standard time cycle for pile driving work

As shown in **Fig. 3**, it took about four hours to drive one pile; therefore, it was theoretically possible to drive two piles per day. There were many days, however, during which in spite of the relatively calm sea conditions in the morning, swells occurred in the afternoon with strong winds and equipment could not be positioned at sea to drive piles. In order to increase the operating time, two piles were positioned in the morning with the diesel hammer at locations where the pile driving barge could be shifted by winch operation. These piles were then driven deeper in the afternoon by using the air hammer, which is less susceptible to the effect of sea conditions. As a result, the rate of pile driving was 1.63 piles per working day.

Table 5 Operation record of pile driving

			1981 Oct.	Nov.	Dec.	1982 Jan.	Total	Remark
A	Calendar day		31	30	31	23	115 days	
B	Working day		15	14	13	18	60 days	$B/A=53\%$
C	No working day		16	16	18	5	55 days	
D	Reason for non-working day	Bad weather	8	13	15	4	40 days	$D/A=35\%$
E		Other reasons (Maintenance etc.)	8	3	3	1	15 days	$E/A=13\%$
F	No. of driven piles (pcs)		18	27	17	36	98 piles	
G	No. of driven piles / Calender day		0.58	0.90	0.55	1.5	0.85 piles/day	
H	No. of driven piles / Working day		1.20	1.93	1.31	1.89	1.63 piles/day	

Table 5 presents the operation record of pile driving.

4.2 Pile Driving Accuracy

Before pile driving, a maximum deviation of 30 cm from the design position was established as a target for the pile driving accuracy (plan position) in view of the difficulties in offshore pile driving. The deviation in inclination of the vertical axis of the pile was set 4% maximum. Since the superstructure was designed with a range of pile driving location and alignment tolerance of 10 to 20 cm, the superstructure design was checked for piles in which this range was exceeded.

For the location of a steel pipe pile at the proper position to be driven, a survey check was made from two directions; i.e., from the bow and side of the pile driving barge. An offshore surveying platform was also installed at sea in advance and a reference point was established for pile location from a control point on land and was marked on the platform.

Pile locations were observed from the offshore surveying platforms using transits, and the pile driving barge was guided with transceivers.

The location of the pile was also checked from the land using a transit from the direction at a 45° angle with the reference points on the bow and side of the barge. At the same time, distance measurements were carried out from a suitable position on the trestle using a light-wave distance meter.

Three offshore surveying platforms were fabricated so that the pile driving operations with the pile driving barge might not be impeded by the delay of survey work. They were used efficiently in rotation. Furthermore, the reference points for pile location were determined by surveyors and equipment independently of those employed for the location of piles.

Figure 4 shows the distribution of pile driving accuracy measured after pile driving.

4.3 Pile Driving Capacity

The selection of a hammer is important for pile driving. The following conditions were taken into consideration in the hammer selection for this project:

(1) Size and weight of the longest pile: 1 500 mm in diameter × 36 mm in wall thickness × 55 m in length (weight = 71.5 t)
(2) Maximum penetration of the pile: 38 m
(3) Soil conditions: Dense fine sand with N values of 14 to 36 in the intermediate layer and 43 to 50 in the end bearing layer

On the basis of these considerations, the diesel hammer MH-80B and air hammer MRB-2 000 were selected to drive piles into the intermediate layer and bearing layer, respectively.

4.4 Bearing capacity of Large-Diameter Steel Pipe Piles

The bearing capacity of the steel pipe piles was controlled during the work by using a wave equation.[2)] To verify these estimated values, a pile load test was conducted by applying a maximum test load of 815 t to the pile P-16 located at about the middle of the trestle and a maximum test load of 1 470 t to a platform pile.

Figure 5 shows the results of the test on the platform pile. A yield load of 1 100 t and ultimate loads of 1 400 to

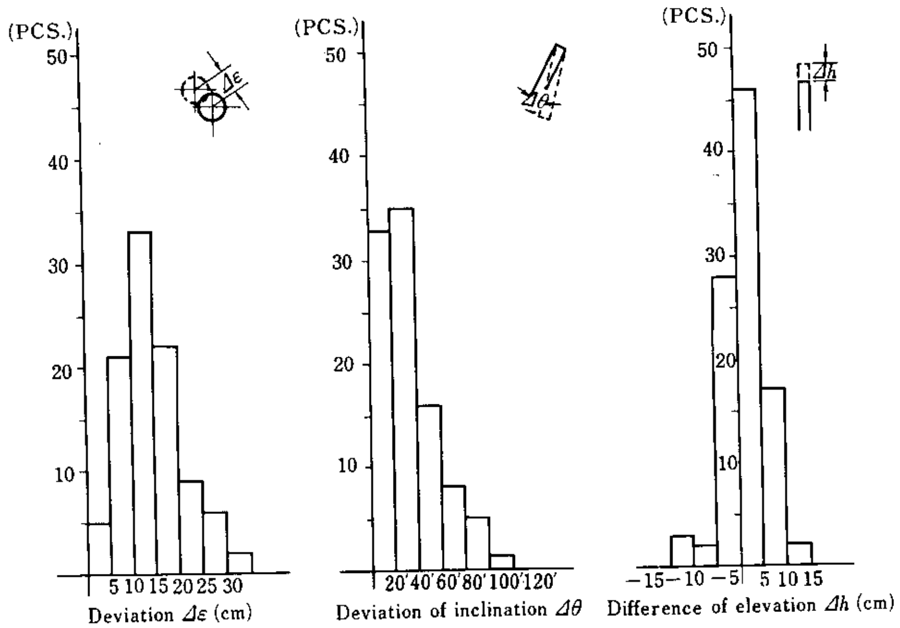

Fig. 4 Deviation obtained by measurement after pile driving

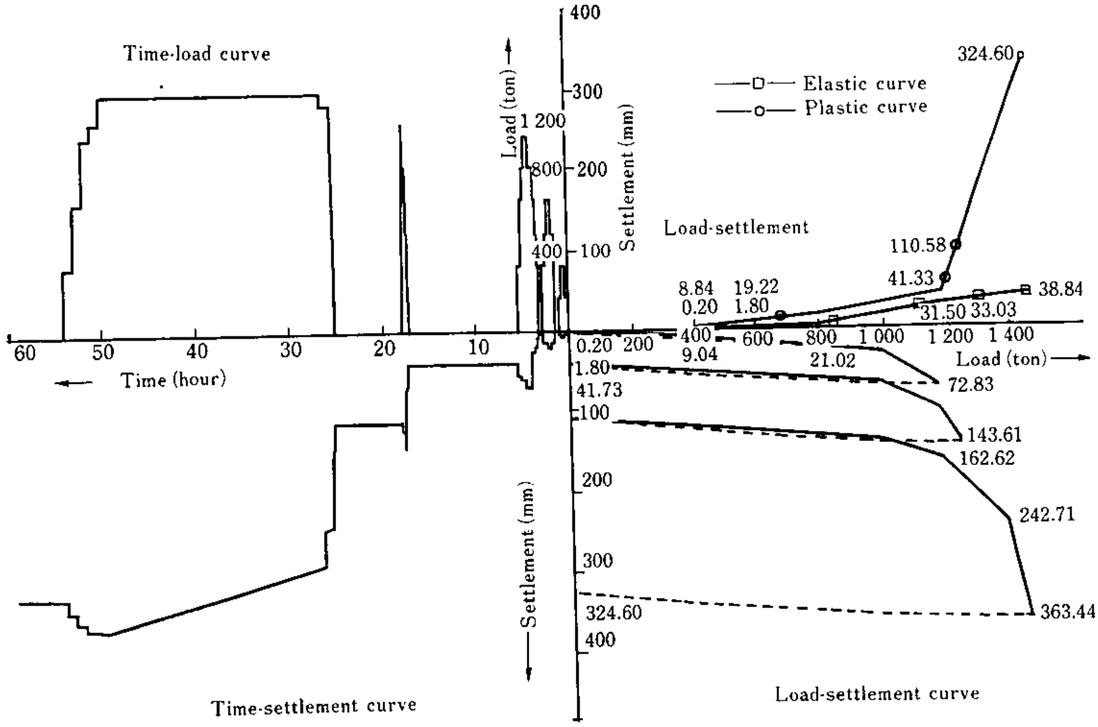

Fig. 5 Load-settlement curve

1 470 t were estimated from these test results. Furthermore, from the results of the measurement of the elastic shortening of the tested pile, it was estimated that the bearing capacity under the maximum test load (1 470 t) consists of friction resistance of 800 t (54%) and point-bearing resistance of 670 t (46%). These values were in very good agreement with the estimated values obtained from the wave equation and those obtained from Meyerhof's static bearing capacity formula.[3]

5 Summary

The application of large-diameter steel pipe piles to offshore structures was described above by referring to the construction of an offshore berth facility for coal unloading in Taiwan. The contents of this paper are summarized as follows:

(1) Field welding of steel pipe
The adoption of tandem submerged arc welding enabled steel pipe to be welded efficiently and with high weld quality.

(2) Driving of steel pipe piles
Although the project site facing the South China Sea experienced severe wave conditions, satisfactory results in the construction time-schedule and pile driving accuracy were obtained by using both a diesel hammer and an air hammer.

(3) Bearing capacity of steel pipe piles
The bearing capacity of steel pipe piles was controlled by estimating it on the basis of wave equation theory during the pile driving work and verifying the estimate with a pile load test. In this pile load test, yield and ultimate loads were confirmed and the bearing capacity mechanism was clarified. It can therefore be concluded that the test results contributed valuable data related to the confirmation of the bearing capacity of large-diameter open-end steel pipe piles.

The offshore berth facility was finally completed in March 1983. In the construction of this full-scale offshore structure, the Engineering Division of Kawasaki Steel as the prime contractor for this project is pleased that this offshore facility was successfully completed with the cooperation of the owner, consultant and local contractors, and would like to extend its sincere gratitude to all the parties concerned in Taiwan and Japan for their guidance and assistance.

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