NIPPON STEEL & SUMITOMO METAL TECHNICAL REPORT No. 115 JULY 2017

Technical Topic

UDC 627 . 34 : 624 . 159 . 1 : 551 . 466 . 6

Damage by East Japan Earthquake and Tsunami in 2011 to Port Facilities and Their Restoration

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Abstract

Outlined herein are the conditions of the damage to the port facilities of Kamaishi and Kashima Works due to the East Japan Earthquake on March 11, 2011, and the plans and restoration works of the damaged facilities. At both the works, the main cause of the damage was not the earthquake itself but the tsunami caused by it. Due to the studies of restoration measures that started immediately after the disaster and the efforts of the people involved, the facilities were returned to normal operation quicker than others in the nearby regions.

1. Introduction

Of the works of Nippon Steel & Sumitomo Metal Corporation, Kamaishi and Kashima Works were the most heavily affected, especially their port facilities, by the 2011 East Japan Earthquake and the consequent tsunami. This paper describes the damage to the two facilities and their restoration.

2. Damage and Restoration at Kamaishi Works

2.1 Overall situation

The earthquake and tsunami wreaked enormous damage on the Pacific coast area of Iwate Prefecture. Kamaishi Works, located in the middle of the prefecture's coast line, was severely damaged mainly in the port facilities by the huge tsunami that arrived after the quake, but thanks to the exhaustive efforts of the people involved, all the damaged equipment was restored to perfect condition in May 2012, only 14 months after the disaster.

The condition of the damage to port facilities is outlined, and the basic philosophy for quick restoration, the design and specifications of the structures and the methods of reconstruction work are presented herein below. **Photo 1** is an aerial view of the port of Kamaishi including the facilities of the Works.

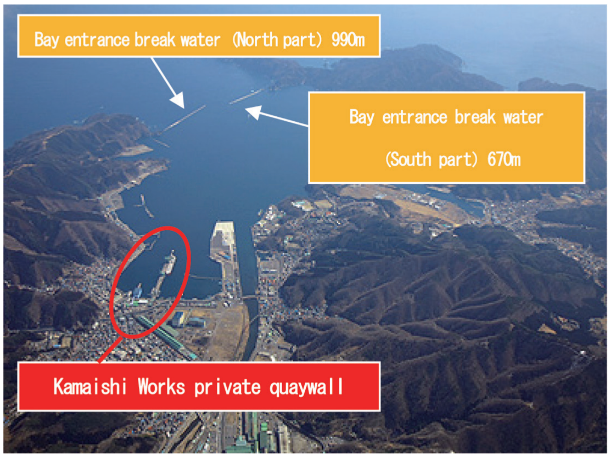

Photo 1 Layout of Kamaishi Port (provided by Kamaishi Port Office)

2.2 Damage to port facilities

The port facilities of Kamaishi Works include the south pier, the north pier (or the all-weather berth) and the center berth. As seen in **Fig. 1**, most of the works' port facilities were heavily damaged: the double sheet-pile walls of the south pier collapsed; the conveyer on it was demolished; the No. 5 crane also on it for unloading billets for wire-rod rolling was partially destroyed; the center berth collapsed; and the building of the all-weather berth was largely destroyed.

2.2.1 Details of damage

The south pier handled raw materials and finished products: billets for the Wire-rod Mill Plant, the main production unit of the works, and the coal for the power plant of the works, which operated also as an independent power producer (IPP), were unloaded from ships, and product wire-rods were loaded onto ships there. The pier was a historical structure 511 m in length. The 200-m portion adjacent to the land was constructed in 1936 with the double sheet-

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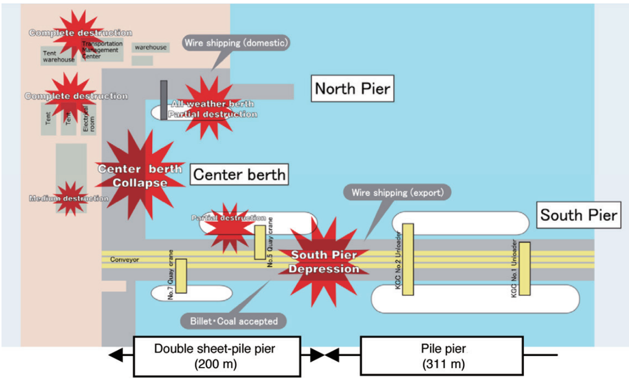

Fig. 1 Damage situation of Kamaishi Works port facilities

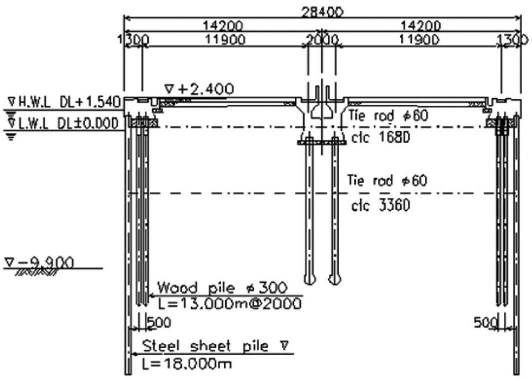

Fig. 2 Section view of south pier

pile wall structure shown in **Fig. 2**; YSP-V sheet piles were used for the double wall, and pine piles for the crane-rail foundations, which served also as the coping. The extension beyond the 200-m portion, the first 138-m long portion and the second 150-m portion being constructed in 1969 and 1979, respectively, was a pier composed of steel pipe piles. The water depth was 9.5 m along the 200-m double-sheet-pile portion, and 14 m along the entire extended portion to accommodate cape-size bulk carriers of coal.

Soon after the quake, depressions more than 1 m in depth, like the one shown in **Photo 2**, were found at different parts of the pier near the end of the double sheet-pile wall portion, 150 to 200 m from the land, and the extent of the damage and distortion of the sheet piles under the water were quickly investigated by a sonar and divers. As a result, the sheet-pile walls were found to bulge beyond the normal limit by more than 3 m, and underwater photographs revealed that many fixing bolts of the lower tie-rods had detached from the sheet piles as seen in **Photo 3**. In contrast, no serious damage was found in the extended pipe-pile bridge portion beyond 200 m from the land.

The center berth, which was reconstructed after being damaged by the tsunami of the Chile earthquake in 1960, was of a wall structure of FSP-III sheet-piles, 16.3 m in length each, with bracing tie-rods. As seen in **Photo 4**, the sheet-pile joints came loose, and many of them fell seawards.

The all-weather berth was a steel-frame building for the loading of wire-rod products for domestic clients having a span of 35 m. As seen in **Photo 5**, the building structure was severely distorted by a large horizontal force from the sea side.

Photo 2 Sunk apron of south pier

Photo 3 Damage to second tie-rod

Photo 4 Destroyed center berth

Photo 5 Partially destroyed all-weather berth

2.2.2 Presumed causes of damage

There are many visual records of the disasters that occurred in the Port of Kamaishi; one of them taken by the Japan Coast Guard from the building roof of the Kamaishi Port Office clearly recorded the vessel Asian Symphony (5 000 DWT) at the time of the earthquake being loosened from the south pier by the tsunami and hitting the all-weather berth several times. The damage of the berth was presumed to have resulted from the collision.

The same recording showed a backrush of the sea so large that the bases of the revetments (−6 to −8 m) in the port area protruded above the water. From this, the backrush was presumed to be one of the causes of the destruction of the sheet-pile walls of the south pier and the center berth, that is, collapsing of the apron and water rise in the backside of the walls due to the high water, subsequent rapid fall of the water level at the wall front and an additional seaward pull at the wall head due to the backrush presumably led to the collapse of the wall.

2.3 Restoration plan and structural design

The targets for the restoration work were set as follows: enabling the Wire-rod Mill Plant, the main production plant of the works, to return to operation as quickly as possible; and restart of the Power Plant before summer, when the general demand for power would increase. Based on the above, the restoration of the south pier was given the first priority to secure the coal supply to the power plant.

2.3.1 South pier

The most important issue in the restoration of the south pier, the main facility for materials handling, was to select the structural specification and the method for its reconstruction as quickly as possible, at the lowest cost and in the most reliable manner. For this, the damage condition of the pier under the water was examined using a sonar, and the basic reconstruction plan was quickly established through a comparison of alternative specifications.

1) Definition of the smallest possible portion to be removed for restoration

It was decided from the functional and structural viewpoints that the double sheet-pile walls, which had been heavily damaged, would have to be removed. The results of the sonar examination revealed that the portion up to 125 m from the land was sufficiently sound, but the 75-m portion beyond it (125 to 200 m from the land) was earmarked for dismantling. **Figure 3** shows the investigation results obtained by the underwater sonar. Sheet piles were newly driven at the 125-m point, and to reinforce the interface zone, the sea-floor soil was improved by the high-pressure jet mixing method.

2) Pier reconstruction plan in two steps

To shorten the work period, a steel-pipe-pile structure was selected as the portion for reconstruction. However, there was one requirement: the pipe conveyer for coal transport on the pier had to be restored as soon as possible, and as a measure for this, it was decided that in the first step a temporary bridge would be built of H-section steels and a deck plate for the conveyer, which would then be put into operation. Then in the second step, the damaged pier portion would be removed and the steel-pipe-pile bridge built as a permanent structure, with the pipe conveyer in operation.

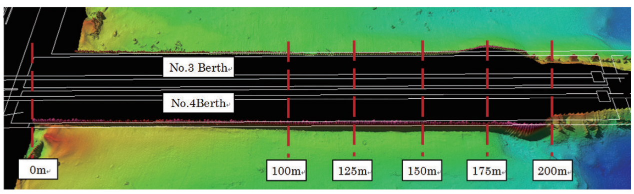

Fig. 3 Findings of underwater sonar at south pier

3) Selection of a viable method for driving steel pipe piles close to the pipe conveyer

To minimize the restoration costs, the portion of the pier to be reconstructed was defined as only the side of the No. 3 berth, 15 m in width, where there was a No. 5 crane. The 45 steel pipe piles, 1 100 mm in diameter and 39.5 m in length each, were arranged in such a configuration to prevent interference with the temporary bridge for the pipe conveyer, and driven well into the bearing layer by a vibration hammer (180 kW), and then, final impacts were applied to them by a hydraulic flying hammer (IHC S-90). **Figure 4** shows a sectional view of the pipe-pile pier, **Photo 6** pile driving by the flying hammer, and **Photo 7** the relation between the pipe conveyer on the temporary pier and the pipe piles after being driven.

4) Treatment of the heads of the steel pipe piles using steel dry boxes

As the entire sea floor of the port of Kamaishi sank by tens of centimeters owing to the earthquake, the heads of the pipe piles would be below sea level, and the quality of the pile head joints to the superstructure was feared to be poor. To secure the weld quality of the joints, a dry space was created for welding work at each pile head using a closed box of steel as shown in **Photo 8**.

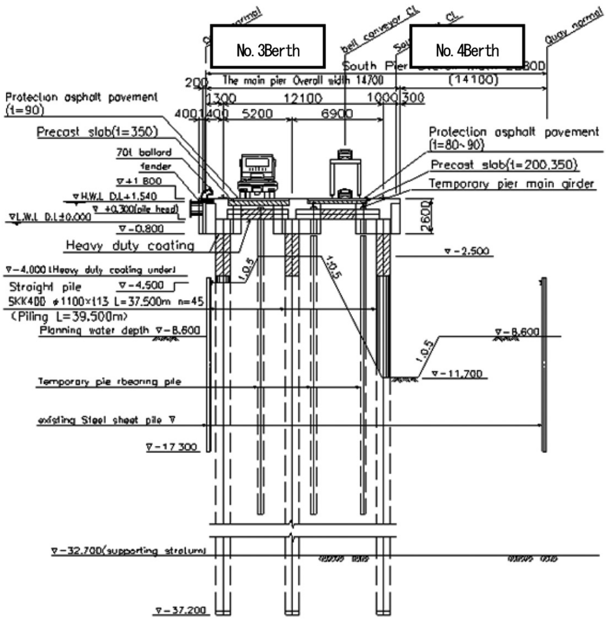

Fig. 4 Repair section view of south pier

Photo 6 Piling by flying hammer method

Photo 7 Restored pipe conveyer and piling work of south pier

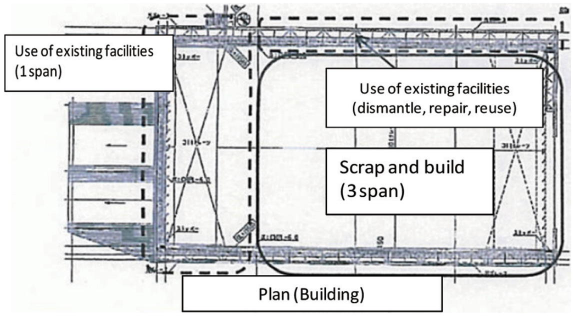

Fig. 5 Repair plan of all-weather berth building (ship accommodated in lower half of building)

Photo 8 Pile head treatment by dry method using the steel box

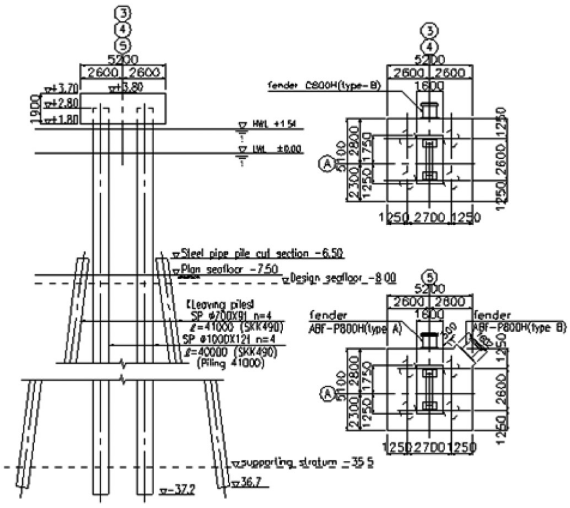

Fig. 6 Repair plan of all-weather berth foundation

2.3.2 Building and foundation of all-weather berth

The all-weather berth was responsible for the shipment of wire-rod products to domestic users, and as such, it had to be restored as soon as possible like the south pier.

1) Investigation of berth building in detail and definition of reusable portions

Regarding the berth building, the total length of which was 60 m, the walls and the roof of the 45-m-long portion on the water side (marked with a round-cornered solid box in **Fig. 5**, in which the building faces the sea on the right and the lower sides) were distorted and collapsed towards the water as a result of the collision of the ship and the destruction of some of its foundations embedded in the sea floor. It was decided that the undamaged building portion would be examined in terms of structural soundness and the parts judged to be reusable would be used for the restoration.

The foundations, the planar distortion and flatness of crane girders and rails, the alignment of columns, the distances between them and the torsion and bend of the members were examined, and the sea-side portion 15 m in length and a land-side portion 60 m in length (each enclosed in dotted lines in Fig. 5) were judged to be reusable. As a conclusion, it was decided that the above-mentioned 45-m-long portion on the sea side shown in Fig. 5 would be dismantled.

2) Damage evaluation of foundations and restoration plan

Three of the five dolphin-type foundations of the berth building on the sea side were extremely distorted in the underwater parts and their footings sank under the water. They were supported by oblique steel pipe piles 800 mm in diameter each, but from the mode of the distortion, pulling them out to remove them was difficult; therefore, they were cut at the sea-floor level, and two pipe piles were newly driven for each of the three foundations, vertically between the old oblique piles as illustrated in **Fig. 6**. This time, the pile diameter was increased to 1 000 mm so that the horizontal rigidity would be the same as that of the old oblique piles. By this, it became possible to restore the berth building in the same structure as before and reuse some of the old structural members. To shorten the work period, prefab footing units were used for the building foundation.

3) Removal of damaged building portions and the method of restoration

Since the building was largely distorted towards the water surface and in an unstable condition under the tension towards the sea, it was necessary to remove the damaged parts without causing the sound portion to collapse and avoid adverse effects on the parts to be reused. To this end, a temporary structure was erected inside the building to support the roof from below, tension wires were provided to prevent the structure from distorting further, and distorted parts were joined or reinforced to sustain the structure and protect the parts to be reused against damage by spring back of nearby members due to sudden tension removal (**Photo 9**). To reduce loads on the structure, the dismantling was started with the roof, and by flame-cutting the parts to be removed manually by providing a gondola for the personnel and holding the parts from above with a movable crane.

New structure frames were installed using a 400-t crawler crane capable of handling fabricated frame pieces of regular size in a normal working radius over the existing structures. Thus, the building was restored to high dimensional accuracy, in which work parts were assembled sometimes piece by piece while their alignment and

Photo 9   Temporary structure for repairing building

levelling with reused portions were confirmed.

3. Damage and Restoration at Kashima Works

3.1 Overall damage condition

Kashima Works is located on the Pacific coast of Ibaraki Prefecture, about 90 km east-northeast from the center of Tokyo. At the time of the East Japan Earthquake, a ground surface acceleration of 658 gal was recorded at a nearby location, and the plants and infrastructures of the works suffered severe damage. While soil liquefaction caused significant adverse effects on some structures with deep foundations, plant buildings and other important structures were not heavily damaged except for some minor problems. On the other hand, the product shipment area was engulfed by a tsunami about 80 cm above the ground, and the quay walls of steel sheet piles were significantly distorted at different locations along the berths for materials unloading and product loading, amounting to a total of 4.1 km.

3.2 Damage to port facilities and restoration plan

3.2.1 Damage to port facilities

Figure 7 shows the layout of the entire works, and **Table 1** outlines the port facilities and the damage inflicted on them. One of the characteristics of the damage by this earthquake is that, besides the damage to structures by the seismic force, tsunami and ships unleashed by it struck the cranes and other port facilities as in the case of Kamaishi, which added to the purely seismic damage. **Figure 8** shows the change in the tide level at a seawater intake of the works; the water sank to as much as 6 m below the datum level (DL) at the lowest. The drifting of many ships by the tsunami was confirmed later with photographs and word of mouth. **Photo 10** shows a loading crane for export products that collapsed after being hit by a drifting ship, and **Photo 11** shows a damaged quay protection of steel sheet piles due to the ship collision.

The reason for the comparatively light damage to the deep-water berths for raw materials unloading and export product shipment is presumably that the port of Kashima was constructed not by landfill

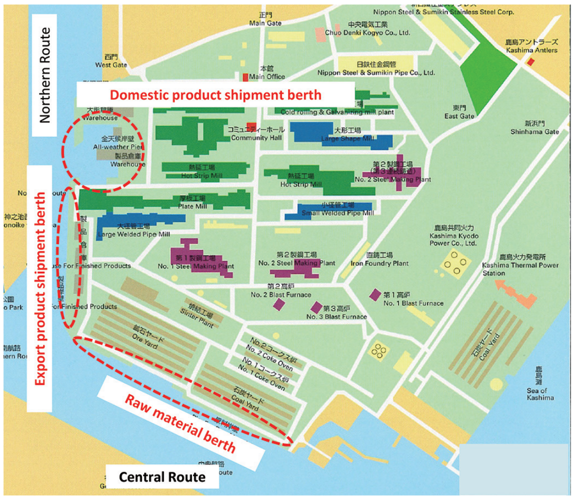

Fig. 7   Layout of Kashima Works

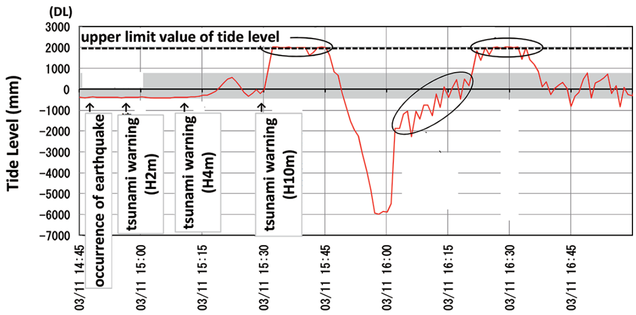

Fig. 8   Time-series tide lebel data on IPP plants

but by excavation into gravel ground, and soil improvement measures had been taken in the backland areas to prevent soil from running off. As a result, large ground distortion due to soil liquefaction did not take place (see Table 1).

In contrast, liquefaction and lateral flow of soil occurred in some parts of the backland of the berth for domestic product shipment, and the sheet pile wall partially inclined toward the sea beyond the normal line (see **Photo 12**). This is presumably because the soil was of comparatively loose sand, the backrush of the tsunami dug into the sea boom in front of the wall, and at the same time, water remaining on the land increased the pressure from behind.

3.2.2 Restoration plan

While it was important to rehabilitate the port facilities in close coordination with the restoration plans of steel production lines, for higher freedom of transport on land and sea, the port facilities had to be returned to working order as soon as possible.

In consideration of the above and through close conversation

Table 1   Damage situation of berths

Berth	Berth length	Water depth	Principal damage
Raw material berth	1 824 m	−14 to −19 m	• Failure of steel pipe sheet pile joints • Shallowing of sea bottom by sand of tsunami
Export product shipment berth	1 100 m	−12 m	• Steel pipe sheet piles damaged due to ship collision • Failure of steel pipe sheet pile joints
Domestic product shipment berth	1 170 m	−7.5 m	• Berth line bulging towards the sea • Failure of steel pipe sheet pile joints

Photo 10 Damage to shipping crane

Photo 11 Damage to shore protection facilities due to collision with a vessel by the tsunami

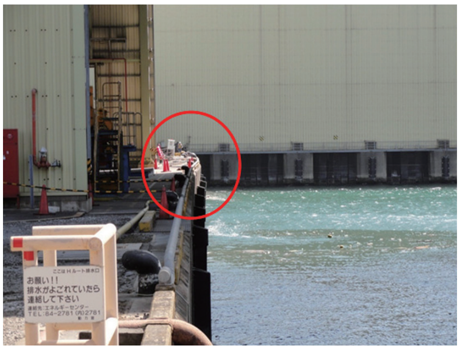

Photo 12 Displacement of the berth line (berth 2)

with the people responsible for the recovery of sea transport, the following was decided: it would be sufficient to restore the berths for raw materials unloading and export product loading by the end of 2011, because another berth remained intact, which could be used as a substitute; and regarding the berth for product shipment for domestic users, the load bearing members for the docking of ships would have to be restored by the middle of August 2011. The work of auxiliary facilities such as pavement of aprons, etc. that would not hinder the loading operation would be finished by the end of September 2011. The background to the above was that, while land transport had been increased to compensate for the loss of sea transport, there were no alternative facilities for sea transport in the works premises, and the damaged berth was also used for the joint operation of RO-RO vessels with Hyundai Heavy Industries, Korea.

The restoration work of the berth for product shipment for domestic users, where the coping was distorted and tilted beyond the

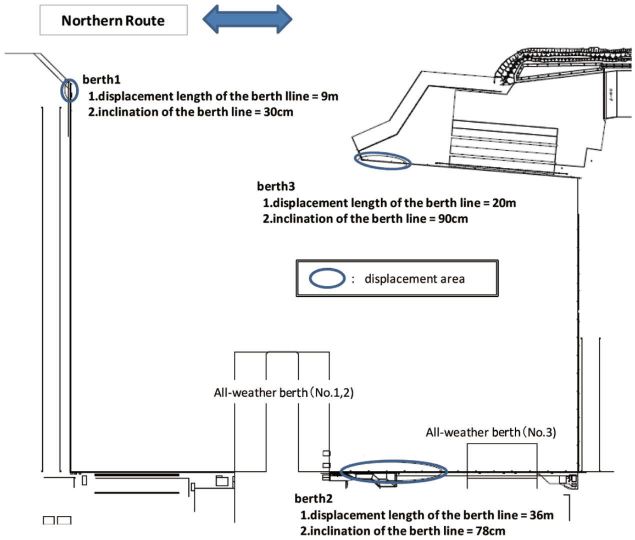

Fig. 9 Damage to product shipping berths

normal line of the berth toward the sea, is reported below.

3.3 Study of structures to be restored, work plan and results

3.3.1 Study of structures to be restored

As illustrated in **Fig. 9**, ships enter the bay of the domestic product shipment berth from the north route of the Port of Kashima. According to the port plan, the quay was to have the tie-rod-and-bracing-plate structure or similar for a water depth of DL−7.5 m to accommodate 4000-DWT vessels. The damage to the quay was as follows: in portions about 65 m in total along the normal limit, the coping distorted and fell projecting toward the sea by 90 cm beyond the normal limit at the largest (see Fig. 9 and Photo 12). As the failure of the tie rods and the dislocation of the bracing plate were suspected to have caused the quay distortion, the bracing structure was investigated by excavation, but no such serious problems were found.

Then there were two alternative reconstruction methods: whether to reinforce the quay wall on the front (sea) side of the normal line or on the back (land) side. In the former case, however, the normal dimensions of the quay wall would have to be changed, which meant that there would be new restrictions to ship maneuver, all of the quay wall had to be reconstructed along the entire length including undamaged portions, the costs would surpass the budget, and the work would not be completed by the deadline date. Thus, the latter alternative was accepted as the basic policy.

Following the basic policy to reinforce the quay from the land side, it was therefore necessary to choose the most economical work method based on the configuration wherein the quay wall is unified with newly introduced reinforcement frames and tied to the bracing structure as shown in **Fig. 10**. As a result of studies, the structure shown in **Fig. 11** was selected, by which the number of the steel pipe piles and the weight of the RC structure, which connected the pipe piles to the quay wall to form the reinforcement frame, were minimized. **Figure 12** is a sectional view of the quay structure after the restoration according to the final design, according to which, the main earth pressure and the tractive force of a moored ship towards the sea were taken care of by the pulling resistance of the oblique pipe piles, and their embedding depth was set so that they had sufficient strength even if the tie-rods-and-bracing-plate structure was broken and failed to function. Note here that the oblique piles were

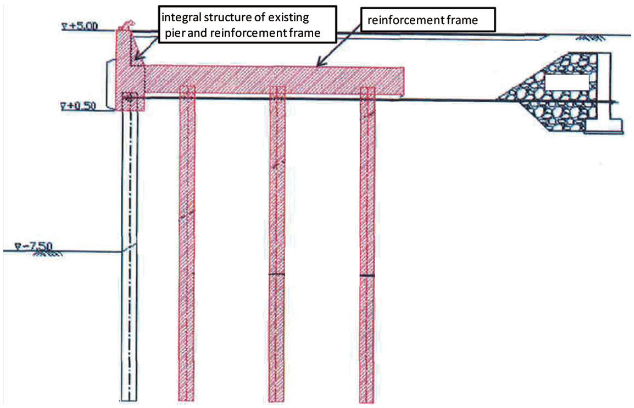

Fig. 10 Basic idea for restoration of quay structure

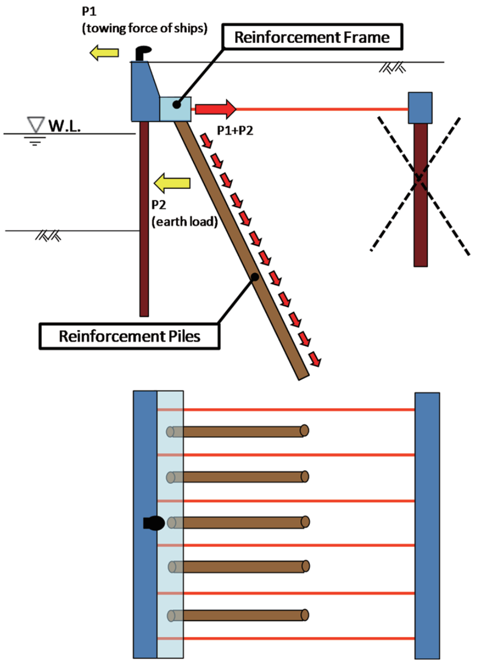

Fig. 11 Schematic illustration of final restoration plan

arranged between the existing tie rods.

3.3.2 Work plan and actual execution

An important issue in the restoration work was that the procurement and driving work of the pipe piles constituted a critical factor in the entire work schedule, and it was imperative to finish the piling work in as short a time as possible to complete the restoration by the deadline date. A total of 35 steel pipe piles, 1 000 mm in diameter and 40.5 m in length, at the largest, weighing 313 t, had to be prepared. According to the reconstruction plan, the pipe piles were to be driven obliquely from the sea towards the land, and a pile driving boat had to be hired for the work.

As for the procurement of the piles, it was considered advantageous and efficient, from the viewpoint of the ease of delivery, to order them from a group company, Sumikin Weld Pipe Co., Ltd. (now Nippon Steel & Sumikin Spiral Pipe Company, Ltd.) because the company has a plant just on the other side of the Center Canal of the port opposite the works. Through negotiations, it was decided that all the piles would be delivered by the end of May 2011.

The contractor for the quay reconstruction work then searched

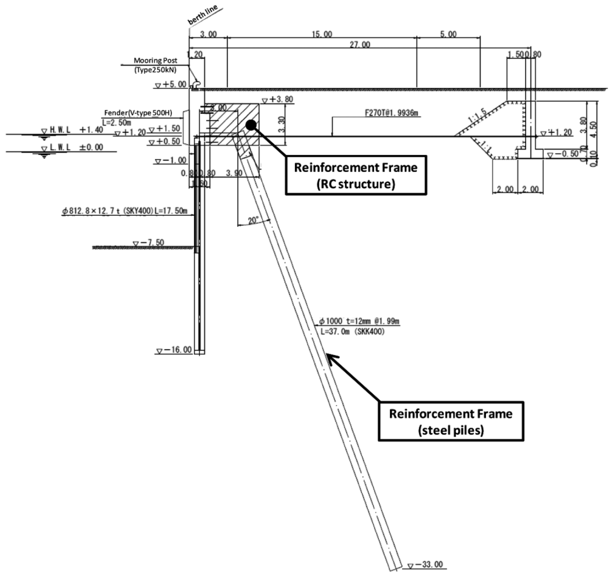

Fig. 12 Details of final restoration plan

Photo 13 Piling work

Photo 14 Reinforcement bar work

for a pile driving boat all over Japan, and as a result of coordination between the different processes, preparatory works were scheduled so that the pile driving would be completed in 16 days from June 10 to 25. **Photos 13–15** show the stages of the reconstruction work from pile driving to the completion of the restoration work.

In addition, quay walls composed of steel pipe sheet piles broke in several places owing to the failure of pile joints. They were repaired by applying reinforcing steel plates to the front (sea) side, and the soil on the back side of the broken wall parts was improved by the high-pressure jet mixing method.

Photo 15 Completion of restoration work

Photo 16 All-weather berth after restoration

Photo 17 South pier after restoration

4. Closing

The damage to the port facilities of Kamaishi and Kashima Works due to the East Japan Earthquake and the measures to quickly return them to normal working order were explained.

At Kamaishi Works, the reconstruction of the all-weather berth was completed on March 11, 2012, exactly one year after the earthquake, the pipe conveyer of the south pier was returned to operation on September 1, 2011, and the entire pier on May 10, 2012. **Photo 16** shows the all-weather berth after the completion of the restoration work, and **Photo 17** the south pier after the reconstruction.

At Kashima Works, thanks to work execution following the efficient restoration plans presented above, the restored port facilities were handed over to the organizations responsible for their operation. The restoration work of the berth for product shipment for domestic users was completed on September 30, 2011, and the same of all the other damaged facilities by the end of the year, as initially planned.

Acknowledgements

The large-scale restoration work performed in parallel at two steelworks, Kamaishi and Kashima was unprecedented. Nippon Steel & Sumitomo Metal is deeply grateful to the people involved, especially those of Penta Ocean Construction Co., Ltd., Obayashi Corporation, Taihei Kogyo Co., Ltd. (now Nippon Steel & Sumikin Texeng. Co., Ltd.) and Nikken Sekkei Civil Engineering Ltd., who, despite the precarious accommodations and frequent after-shocks, conducted the damage investigation, planning and site works for the restoration of the port facilities.

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