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Coastal Dyke and Tide Barrier Technologies for Large Earthquakes and Tsunami Runups

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Abstract

Nippon Steel & Sumitomo Metal Corporation researches and develops solution technology related to the reinforcement and renovation of coastal protection facilities, such as coastal dykes and tide barriers, as the countermeasure against large earthquake and tsunami such as Nankai Trough Earthquake, which is concerned to occur in the near future. This paper reported the research and proposal case about the reinforcement of coastal dykes against earthquake and tsunami using steel sheet-piles which are excellent in toughness and strength. And then, this paper reported that upright precast type tide barriers, which can be constructed even in lack of material and labor, and expected high tenacity against disasters with steel pipe pile foundation, was put on the market.

1. Introduction

Coastal protection facilities must have sufficient structural stability to withstand multiple disasters, including earthquakes and tsunamis, and particularly gigantic earthquakes, such as the Nankai Trough Earthquake, which is highly likely to occur in the near future. Considering the serious lack of construction materials and labor for earthquake disaster reconstruction in the Tohoku region, there is a growing need to incorporate structural features that minimize the labor required. In this paper, we introduce technology solutions such as labor-saving structural features that combine the use of steel sheet and steel pipe piles that have excellent toughness and strength with precast concrete members to construct specific coastal dykes and tide barriers that can resist liquefaction-related damage or tsunami forces.[1, 2] These solutions can reduce structural deformation and damage following a major earthquake and facilitate the rapid construction of structures that can mitigate damage inside dyke areas without failure against post-quake tsunamis.

We focus on coastal dyke reinforcement with double steel sheet pile walls and an upright precast tide barrier. Of the available reinforcement or renewal technologies, we describe the use of steel sheet piles or steel pipe piles as a recent technical advance against gigantic earthquakes or tsunamis, and explain their development and application in national disaster prevention projects and in earthquake disaster reconstruction in the Tohoku region.

2. Coastal Dyke Reinforcement with Double Steel Sheet Pile Walls

2.1 Case examples of applications with and without damage from the Great East Japan Earthquake

Photo 1 shows a coastal dyke damaged by the Great East Japan Earthquake and Tsunami (2011). Although this post-earthquake tsunami devastated the dyke, a double steel sheet pile wall structure being used as a temporary cofferdam in Iwate prefecture is reported to have survived the tsunami, as shown in **Photo 2**. This structure was hit by post-earthquake tsunamis estimated to be 9 m in height, which far exceeded the crown of the structure in the direction orthogonal to that of the tsunami, while maintaining its function and remaining intact.[3] Although the filling soil was drained and the ground in front of the steel sheet piles was scoured by the tsunami, the steel sheet pile walls and the tie beams connecting the steel sheet piles endured.

Here, we focus on the tenacity of double steel sheet pile walls against gigantic earthquake and tsunamis, and attempt to solve a number of technical problems in order to establish a coastal dyke

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reinforcement method, as shown in **Fig. 1**.

2.2 Identification of technical problems

2.2.1 Establishment of the deformation verification technique with respect to gigantic earthquakes

Although there are techniques for predicting the deformation of a structure hit by an earthquake in order to verify the earthquake-resistance of a coastal or river dyke, as yet, the reinforcement effect of a double steel sheet pile dyke in response to a gigantic earthquake such as the predicted Nankai Trough Earthquake has not been fully verified. For these circumstances, we conducted a reproduction analysis using a shaking table model experiment and a dynamic effective stress analysis to establish a deformation verification technique that is applicable to gigantic earthquakes with a high acceleration amplitude and a long duration, and quantitatively evaluated the enforcement effect.

2.2.2 Evaluation of structural stability against overflow tsunami

In structural design, it is standard procedure to test the expected tsunami wave force on a dyke with respect to hydraulic distribution. However, there has been no evaluation yet of the structural behavior of a double steel sheet pile dyke subjected to tsunami overflow. Therefore, we conducted a hydraulic model experiment to study tsunami overflow, verify structural behavior, and better understand the reinforcement effect.

2.2.3 Evaluation regarding multiple disasters with continuous occurrences of earthquakes and tsunamis

While past research has validated the integrity of structures against individual disasters such as earthquakes, tsunamis, or storm surges, it is necessary to consider multiple disasters to comprehensively evaluate the disaster prevention and mitigation performance of structures, since tsunamis occur shortly after the occurrence of earthquake damage in some areas. Here, we use numerical analysis to evaluate the reinforcement effect of the reported structure (tenacity) against a series of multiple disasters, including earthquakes and tsunamis.

Photo 1 Suffer example of coastal dykes [4]

Photo 2 Tsunami suffer example of double steel sheet pile walls

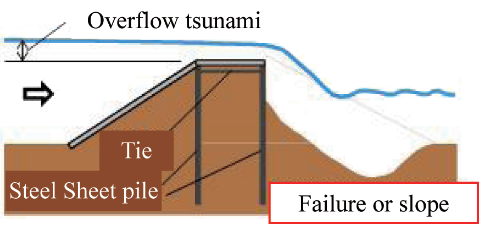


Fig. 1 Reinforcement for coastal dykes against overflow

3. Research and Development

3.1 Establishment of structural analysis evaluation technique for gigantic earthquakes [5]

3.1.1 Vibration table model experiment

(1) Experimental conditions

To establish a numerical analysis technique, we conducted vibration-table model experiments (1G), with a geometric scale λ of 1/25, to acquire measurement data on the deformation behavior of reinforcement structures. The experimental conditions are shown in **Table 1** and **Fig. 2**. We used the wave observed during the Great East Japan Earthquake (K-NET Kamaishi) (**Fig. 3**) as the seismic wave input, and adjusted the duration time, in preparation for developing a strategic response to a future gigantic earthquake.

(2) Experimental results

Photo 3 shows the condition of the deformed dyke after the experiment. Even after the ground is liquefied by vibration, the deformation and settlement of the dyke and the ground surrounded by the sheet piles was mitigated. Furthermore, since the depth of the sheet piles extended into the unliquefiable layer, almost no settlement occurred to the sheet piles themselves, and the top level of the structure was maintained.

Table 1 Size of levee, ground and countermeasure

	Coastal dykes height	Liquefiable layer	Unliquefiable layer	Countermeasure
Prototype	7.5 m	8 m	5 m	Hat-type steel sheet pile 900 (25H)
Test model	300 mm	320 mm (Dr=45%)	200 mm (Dr=90%)	Steel plate (t=3.2 mm)

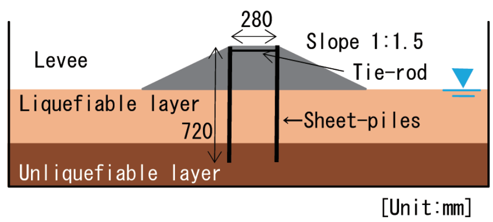


Fig. 2 Cross section of test model

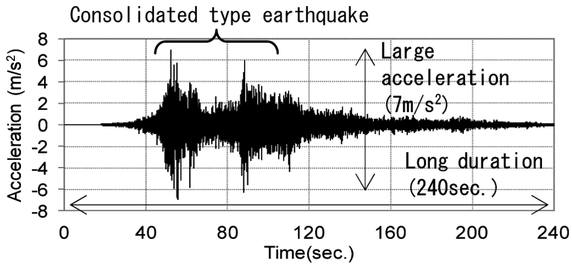


Fig. 3 2011 Tohoku Region Pacific Coast Earthquake (K-NET Kamaishi)

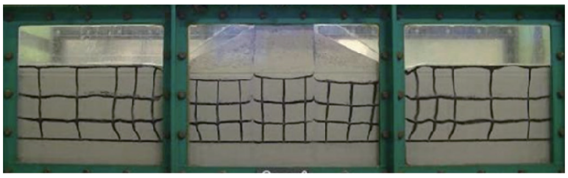


Photo 3 Levee deformation in model test

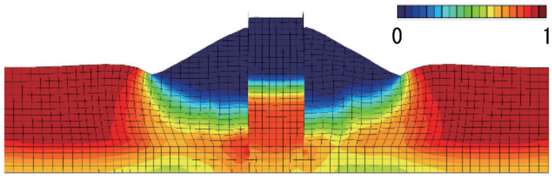


Fig. 4 Levee deformation with excess pore water pressure ratio in analysis

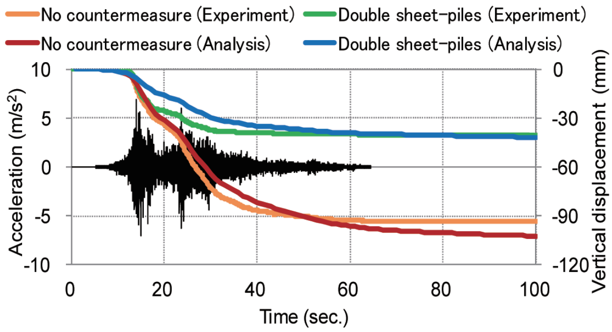


Fig. 5 Time histories of vertical displacement at top of levee

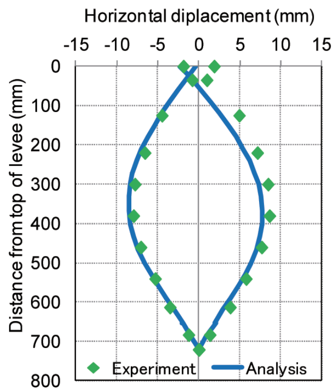


Fig. 6 Bending deformation of sheet-piles

3.1.2 Reproduction numerical analysis

Based on the results of the vibration-table model experiment, we conducted a reproduction analysis using a two-dimensional dynamic effective stress analysis code (LIQCA2D12), which is widely used in liquefaction problems, to evaluate the validity of this analysis technique.

Together with the deformation condition of the dyke, **Fig. 4** shows the excess pore water pressure ratio $\Delta u/\sigma_{vo}'$ contour (80 s after vibration). Although the ground was liquefied, as in the model experiment, the sheet piles demonstrated their settlement mitigation effect. Along with the results of the case without reinforcement, **Fig. 5** shows the time history of the vertical displacement of the dyke crown. Settlement started to occur at around 15 s, when the acceleration amplitude began to increase, with or without sheet piles. We can see that at around 25 s the acceleration amplitude began to increase again, and the settlement amplitude of the dyke crown became smaller in the reinforcement case than in the case without reinforcement. As the seismic motions continued, and deformation progressed in the case without reinforcement and reached a residual settlement of about 95 mm. In contrast, settlement progressed only a little in the case with reinforcement, and residual settlement was 42 mm, less than half that of the case without reinforcement. **Figure 6** shows the residual deformation of the sheet piles. In this exercise, we precisely reproduced the behavior of the steel sheet piles bending toward the outside of the dyke as the ground deformation progressed.

When seismic motions influenced the dyke while the ground was liquefied, the dyke without reinforcement experienced a serious progression of damage. However, the dyke reinforced with double steel sheet piles exhibited a high level of deformation and settlement control against these seismic motions. In the above series of evaluations, good reproducibility was demonstrated with respect to the deformation condition or reinforcement effect of the dyke reinforced with the double steel sheet piles. Finally, we successfully established a deformation prediction technique for gigantic earthquakes characterized by a high acceleration amplitude, long duration time, and chain occurrence.

3.2 Verification of tsunami-resistant performance with hydraulic experiment [6)]

(1) Experimental conditions

We placed a model of a dyke with a geometric scale of 1/50 in an open channel 450 cm long and 15 cm wide, with a horizontal gradient, and conducted an experiment by running a constant flow of water with adjusted overtopping depths (**Fig. 7**). **Table 2** lists the experimental conditions. To verify the reinforcement effect of the steel sheet pile structure under the most severe conditions that totally destroy the interior slope of the dyke, we conducted this experiment without covering the dyke with concrete. Considering the recent research trend that suggests the possibility of scouring contributing to the energy absorption of tsunami overflow, we examined the effect of mitigating the tsunami force.

(2) Experimental results

1) Tsunami-resistant performance of the reinforced dyke

Figure 8 shows the shape of the dyke and sheet piles used in the experiment. Without reinforcement, the entire dyke rapidly corroded immediately after the start of the overflow. With steel sheet pile reinforcement, scouring began on the rear slope soon after the start of the overflow, and eventually the sheet piles slightly slanted. Howev-

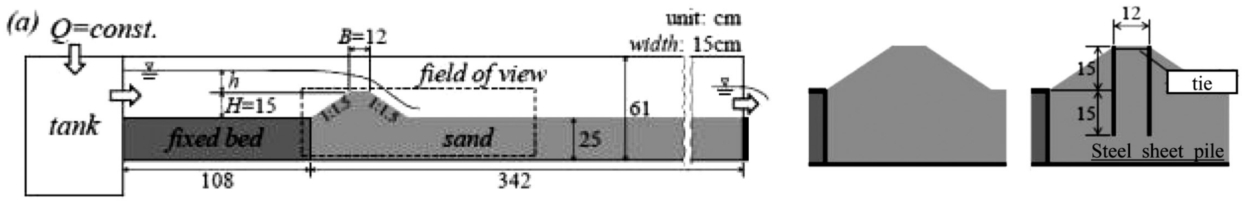


Fig. 7 Hydraulic experiment model

Table 2 Experimental conditions

	Coastal dykes			Countermeasure	Overflow time
	Height	Breadth	Slope gradient		
Prototype	7.5 m	6.0 m	1 : 1.5	Hat-type steel sheet pile 900 (25H)	10 min
Test model	15 cm	12 cm	1 : 1.5	Steel plate (t = 1.6 mm)	85 s

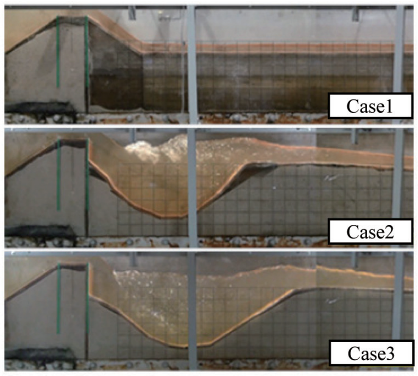


Photo 4 Experiment conditions

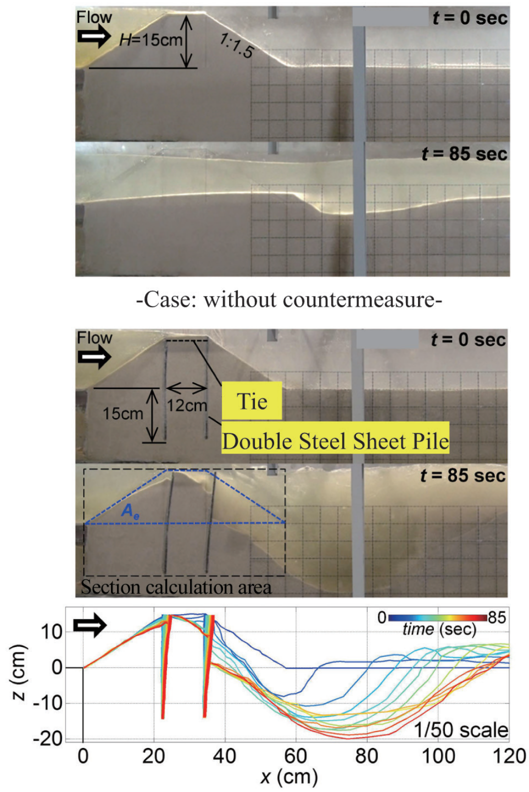


Fig. 8 Coastal dykes reinforcement against overflow tsunami

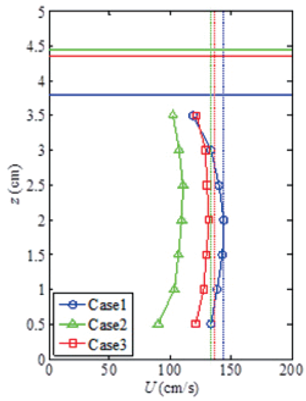


Fig. 9 Distribution of velocity-depth

er, even though the ground height behind the sheet piles neared the ground height of the foundation (z = 0 in the figure), the dyke did not collapse, and the crown height remained almost the same. The dyke height of the double wall structure at the end of the experiment showed a settlement of about 0.3 cm (about 2% of the initial crown height), so there was no significant reduction in dyke height. The measured bending strain of the sheet piles was smaller than their yield strain, which indicates that the sheet piles did not cause the yielding. This result confirms that reinforcement with double steel sheet piles prevented the structure from collapse under severe conditions that caused scouring in the interior ground area of the dyke and allowed the structure to maintain tenacious dyke function.

2) Tsunami force mitigation effect inside the dyke area

Based on the shape data of the scouring obtained from Fig. 8, we produced a water channel model using a fixed bed, and conducted an experiment by running water to the same overflow depth. **Photo 4** shows the experimental conditions, and **Fig. 9** shows the distribution of the average horizontal flow velocity for vertical depth at a position 200 cm downstream (100 m in the actual length). For the case with a scour, differences occurred depending on the shape of the scour after overtopping, but we observed a greater tendency for flow velocity slowdown than in the case without scour.

In addition to the abovementioned influence of the double steel sheet pile structure in reducing the amount of tsunami overflow, the above results suggest the possibility of scour contributing to a reduction of flow velocity in the area inside the dyke. It is reasonable to conclude that structures reinforced with double steel sheet piles have structural serviceability related to tsunami-resistant functions, including the capacity to reduce the amount of tsunami run-up to the land area.

3.3 Performance evaluation for multiple disasters including earthquake and tsunami [7)]

(1) Analytical conditions

Figure 10 shows the structure studied in this subsection. For the seismic motion input, we used the double occurrence Tonankai and Nankai Earthquake wave (Kochi prefecture model) estimated by the Central Disaster Prevention Council (2003) (**Fig. 11**). As an earthquake analysis evaluation technique, we used the analysis code (LIQCA2D13) whose validity was verified in section 3.1. The evaluation included the time to the dissipation process of the excess pore water pressure after the end of the earthquake. Then, assuming the tsunami arrives before full dissipation of the excess pore water pressure from the ground, we conducted a step analysis (Code: ALID) in which we applied the tsunami load to the condition of the ground with reduced effective stress.

(2) Analytical results for earthquake and excess water pressure dissipation

Figure 12 shows the dyke deformation when the earthquake ended and the distribution of the excess pore water pressure ratio Ru ($\Delta u/\sigma_{vo}'$), and **Fig. 13** shows a plot of the time history of the excess pore water pressure. In the ground enclosed by the cofferdam, the dissipation of the water pressure accelerated after the earthquake ended. Ten minutes after the end of the earthquake, the Ru ratio was about 0.8, which reduced to 0.4 and 0.2 after 4 h and 8 h, respectively, and then almost dissipated. With respect to the ground near the sheet piles outside the cofferdam and its effect on the deflection of sheet piles or toppling or sliding of the structure, the Ru ratio increased to about 0.6 when the earthquake ended and its value was nearly the same as that of the ground in the cofferdam, due to the water pressure dissipation thereafter. Even immediately after the earthquake was over, there remained effective stress in the ground around the sheet piles. We presume that a ground reaction corresponding to residual effective stress may be expected in light of the behavior of the steel sheet pile wall that deformed in the lateral direction due to the dissipation of the excess pore water pressure before the arrival of the tsunami.

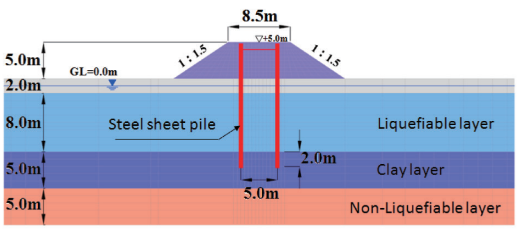


Fig. 10 Analytical prototype model

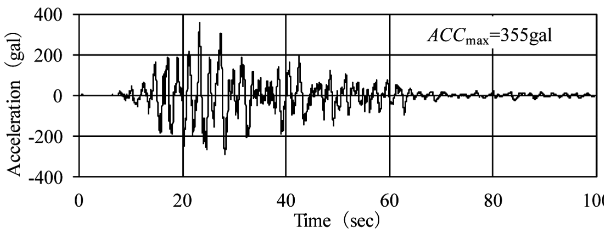


Fig. 11 Input motion

(3) Results of analysis under tsunami force

To simulate the arrival of a tsunami before full dissipation of the excess pore water pressure, we utilized the above analysis results and conducted a further analysis by applying tsunami force under the ground just under the embankment, with a Ru ratio of 0.8, based on the assumption that the tsunami arrives 10 min after the occurrence of the earthquake. We evaluated the ground rigidity of the liquefiable layer as a condition that allows the effective confining pressure to remain at about 20% of the initial value, and for the tsunami loads we applied to the wall the wave pressure proposed in the Tanimoto equation [8)], assuming a tsunami height of 5.5 m. We assumed the dyke slope to move by the impact of the wave forces or scouring by overtopping waves, and applied the tsunami forces (uprush and backrush) under conditions in which the sheet pile side embankment had been removed.

Figure 14 shows the deformation condition when the dyke experienced uprush (first wave). Although a slightly larger deformation occurred from the uprush, the deformation of the embankment surrounded by the steel sheet piles remained minimal even after the second wave, a or tsunami; the structure did not collapse and the dyke crown nearly maintained its initial height. This is presumably because of the shear resistance of the ground surrounded by the sheet piles and the rigidity and strength of the sheet piles resisting the tsunami external force.

Figure 15 shows the depth distribution of the response bending moments of the sheet piles in each of the tsunami force application cases. With respect to the bending moment of the sheet piles, the sheet piles did not reach the totally plastic state, although some piles yielded, which prevented drastic lateral deformation and eventually maintained the structural stability and original functions of the dyke.

These numerical analysis results confirm that dyke reinforce-

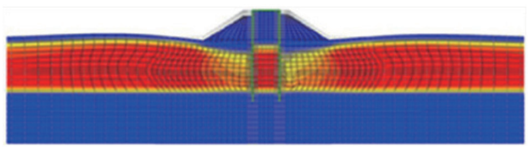


Fig. 12 Deformed configuration and excess pore water ratio counter

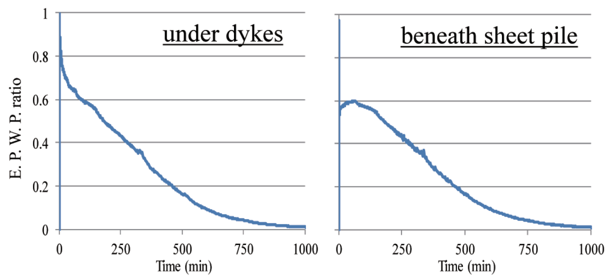


Fig. 13 Time history of excess pore water pressure ratio

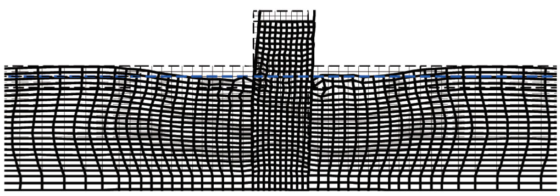


Fig. 14 Deformed configuration of reinforced coastal dykes

ment with double steel sheet piles has a reinforcement effect that makes the dyke a "tenacious" structure that can maintain its crown height and will not collapse even when hit by multiple disasters involving strong quakes, liquefaction of the foundation ground, and the action of tsunami external forces accompanied by overtopping.

3.4 Case example of dyke reinforcement applied with double steel sheet pile wall

As one measure of coastal protection facilities' ability to cope with the Nankai Trough Earthquake, coastal dyke reinforcement work is being conducted using the above reported structure equipped with earthquake- and tsunami-resisting capabilities along the Pacific coasts, particularly in the Tokai and Shikoku areas, to strengthen their realize disaster prevention and mitigation capabilities.

One examples is a seismic retrofit project at the Nino Coast, west of the Katsurahama area, Kochi city, Kochi prefecture, which faces the Pacific, as shown in **Fig. 16** and **Photo 5**. The existing dyke has a crown width of 7.7 m and is about 6 m in height from the surface of the prefectural road behind the dyke. We expect that a major earthquake will cause the sandy layer 7 to 10 m deep under the crown of the dyke to liquefy and that this liquefaction will cause settlement and deformation of the dyke. The eventual reduction in the crown height is of major concern, which would induce devastating damage by tidal surges or tsunamis to the area inside the dyke. As one way to address this problem, dyke reinforcement with double steel sheet piles is being employed.

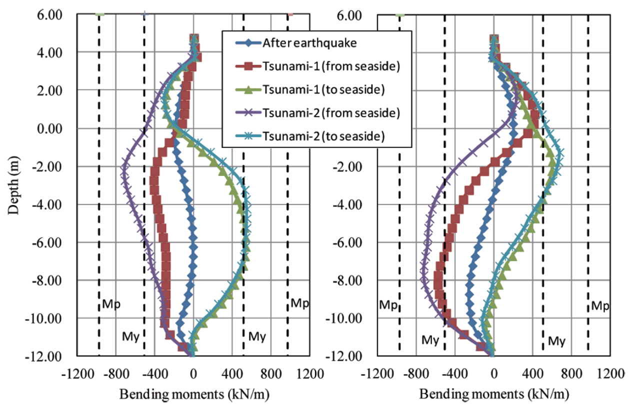


Fig. 15 Bending moments of sheet pile

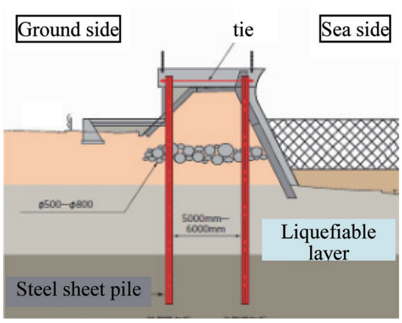


Fig. 16 Cross section

Photo 5 Construction condition

4. Upright Precast Tide Barrier

4.1 Reconstruction following damage from the Great East Japan Earthquake

In this section, we address action related to the upright precast tide barrier. As a result of the Great East Japan Earthquake, a large number of tide barriers failed along the Pacific in the Tohoku region (**Photo 6**). During reconstruction, the height of the coastal dykes was revised significantly in three prefectures damaged by the earthquake–Iwate, Miyagi, and Fukushima. In the coastal area north of the Ojika Peninsula, Miyagi prefecture, there is not much flat land due to the ria coastal topography, so an upright tide barrier was deemed necessary to manage in its small construction area. As the rehabilitation work progressed, the project was plagued by a shortage of materials and labor, including ready-mixed concrete, aggregates, and labor for reinforcement work and formwork. This raised a demand for upright precast tide barriers that minimize the need for local procurement of materials and labor force.

In response to these circumstances, the Nippon Steel & Sumitomo Metal Group established precast tide barrier system structures (**Table 3**) that feature a combination of precast superstructure and a steel pipe pile foundation that provides toughness against earthquakes and tsunamis and is consistent with its commitment to generate optimal structural, design, and construction solutions. Due to their inherent advantages of stability and rapid construction, these systems are increasingly being applied to various projects amid the intensifying shortages of local materials and labor force. Some of these application cases are presented below:

4.2 Case examples of application of the upright precast tide barrier

4.2.1 Fujiwara area of the Miyako Port, Iwate prefecture: Inverted T-shaped precast tide barrier

In the Fujiwara area of the Miyako port, Nippon Steel & Sumitomo Metal Group located a tide barrier of T.P. + 8.5 m behind an industrial area. A 50-m long section of the 1 190-m long tide barrier had been destroyed by the tsunami, and the tsunami overflow caused scouring in some of the back slopes of the barrier. We determined the need for a new tide barrier of T.P. + 10.4 m to be constructed behind a port road in the Fujiwara area of the Miyako port, and construction work is now underway. Due to the lack of ready-mixed

Photo 6 Suffer example of tide barrier [4]

Table 3 Menu of precast type tide barrier

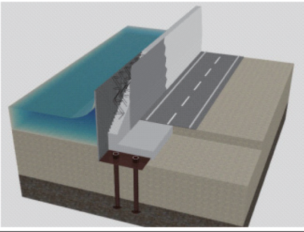
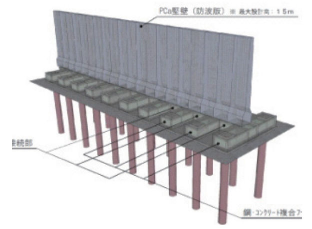
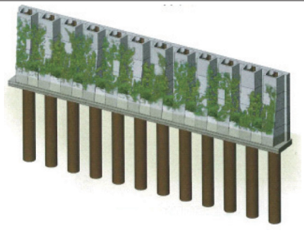
L-shaped precast tide barrier (NIPPON STEEL & SUMIKIN ENGINEERING CO., LTD.)	Inverted T-shaped precast tide barrier (Yokogawa Sumikin Bridge Corp., GEOSTR Corporation)
	
Cantilevered precast tide barrier (Kyowa Concrete Industry Co., Ltd.)	Cantilevered precast tide barrier (Nippon Steel & Sumikin Metal Products Co.,Ltd.)
	

Photo 7 Construction condition of reverse T type precast tide barrier

concrete in the Miyako area, a precast tide barrier was necessary to considerably reduce the local demand for ready-mixed concrete. We investigated a structural option that uses a system of two lines of pipe piles to resist the external forces of earthquakes and tsunamis. Eventually, we adopted an economically efficient inverted T-shaped precast tide barrier is with a steel and concrete composite construction for its footing (**Photo 7**). To drive the steel pipe piles that support the tide barrier, we used the pile driving method as there were no buildings or homes in the port area.

4.2.2 Ohdaira area, Kamaishi Port, Iwate prefecture: Cantilevered precast tide barrier

In 1965, a tide barrier, T.P.+4.0 m in height was constructed in the Ohdaira area, Kamaishi Port coast. The Great East Japan Earthquake caused wide-area ground settlement of this area of about 1 m. In addition, the area suffered catastrophic damage as the barrier failed at several locations during the tsunami. In the Kamaishi bay area, Nippon Steel & Sumitomo Metal Group is constructing new dykes, T.P.+6.1 m in height to resist an L1 tsunami. Considering the fact that offices of an oil terminal and an industrial park are located close by in the hinterland of the tide barrier in the Ohdaira area, it was necessary to minimize the cross-section of the new tide barrier. Therefore, we adopted the cantilevered precast tide barrier, which

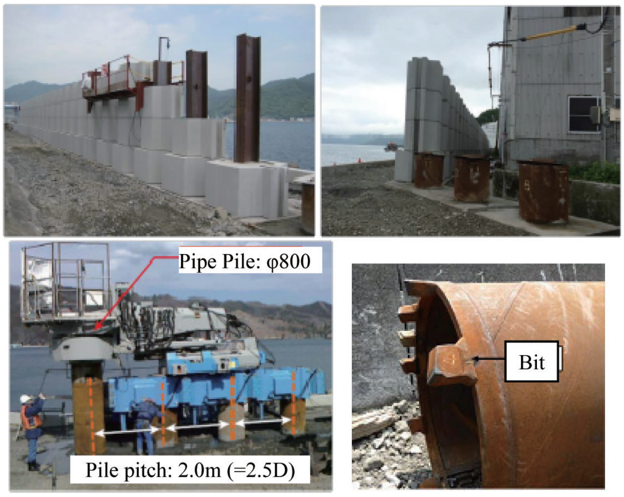


Photo 8 Construction condition of cantilevered type precast tide barrier

requires no footing and can use a single row of piles (**Photo 8**). Since the construction site area was small with hard layers with N values of 50 or more, when the steel piles that support the tide barrier were driven to the ground, we employed the Gyropress method™, which screws piles into the ground by attaching a bit to the front end of the pile.

The new tide barrier is being constructed with steel pipe piles, each 800 mm in diameter, driven at intervals of 2.0 m on the pile centers. We achieved continuous pile-driving while maintaining the predetermined pile-to-pile interval by using the dedicated skip lock attachment, as shown in Photo 8.

5. Conclusion

In preparation for gigantic earthquakes and tsunamis such as the Nankai Trough Earthquake that is predicted to occur in the near future, Nippon Steel & Sumitomo Metal Corporation propose R&D and technology solutions related to the reinforcement and renewal of coastal protection facilities such as coastal dykes and tide barriers. We have proposed various structural systems and technologies that incorporate steel, which are being used in many projects. We intend to continue to develop technical proposals that promote effective and feasible facility renewal and reinforcement using steel infrastructure, including disaster prevention and mitigation projects that build national resilience and reconstruction projects following earthquake damage, thereby contributing to the betterment of society.

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