Technical Report

Double Steel Sheet Pile Walls Having Resiliency Capacity for River Dikes against Long-Time Overflow

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Abstract

Since flood damages are experienced frequently in Japan, "resiliency" of river dikes is required. Nippon Steel Corporation advances the research and development of double steel sheet pile walls (SPWs) to innovate and improve the resiliency of river dikes. SPWs can be applied as quay walls, coastal dikes and temporary cofferdams etc., because of their high lateral resistance against earthquakes, and their excellent seepage cutoff capability. To be adopted as a reinforcement method against the flooding of river dikes, SPWs are required to verify their resiliency capacity against long-time overflow. A hydraulic laboratory experiment of a 1/15 embankment model with SPWs was conducted. The top level of the sheet pile was maintained against an overflow (30 cm overflow depth and 12 hours in proto scale) with scour. In the future, the design method, survey and maintenance method for SPWs having resiliency capacity against long-time overflow will be prepared.

1. Introduction

In recent years, Japan has experienced an increase in devastating heavy rains. Various places in Japan have suffered enormous flood damage, for example, due to heavy rain in the Kanto and Tohoku regions in 2015, that in the northern part of Kyushu in 2017, and that in Western Japan in 2018. In 2019, Typhoon 19 (Hagibis) caused river flooding at the same time in different places over a wide area—mainly in Eastern Japan, causing as many as 142 river dike breaks.[1)]

Against the background of these increasingly severe and more frequent flood disasters, the Japanese government started studying technologies to boost the resiliency capacity of river dikes. The dominant principle is to construct flood control facilities, such as dams and retarding basins, so as to lower the water levels of rivers during floods as much as possible. Based on this principle, the Japanese government also aims to construct river dikes having resiliency capacity as a dike reinforcement measure. Such dikes exert disaster prevention and mitigation effects, for example, they do not easily break even when the rivers overflow for a long period of time and thus, they gain time, albeit a little, until breaking occurs.[1)]

Considering these terrible damages and the government's policy, Nippon Steel Corporation started working on the application of double steel sheet pile walls (SPWs) to river dikes to enhance their resiliency capacity (**Fig. 1**). Technological development of SPWs for temporary cofferdams, coastal dikes, and small earth dams has already been conducted and we are planning to satisfy the performance demanded of river dikes having resiliency capacity using such knowledge. Moreover, it is important that SPWs work well against earthquakes because Japan has frequent earthquakes and after the Great East Japan Earthquake, tsunamis flowed upstream. There are other points to note in addition to measures against flooding and earthquakes. Many river dikes were made from soil and their height and width were repeatedly increased after flooding damage, etc. and thereby the categories of soil nature and the strength distribution are complicated and differential settlement may occur; river dikes require long-term maintenance and management; and they play an important role from the viewpoint of scenery because they are closely related to the lives of people and natural environments in the basin of the rivers.[1)] Considering these various aspects of river dikes, we have been working on technological development so as to propose comprehensive solutions by combining economical

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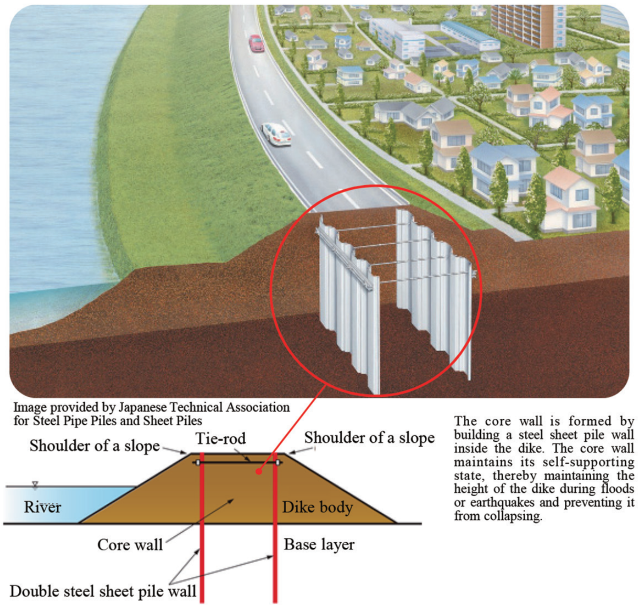


Fig. 1 Double steel sheet pile wall for river dikes

hat-type steel sheet piles and high-level steel structure technologies with materializing resiliency capacity against long-time overflows.

2. Technological Development for SPWs Up to Now

SPWs are constructed by placing steel sheet piles (including steel pipe piles) in two rows to form walls, tying the heads with tie rods, and charging filling materials (e.g., ground materials) into the space between the steel sheet pile walls (hereinafter, "core section"). **Table 1** lists the dike types to which SPWs are applied and design manual preparation. The basic structure and design method of SPWs were established as the structure of temporary cofferdams using double steel sheet pile walls.[2] Temporary cofferdams are makeshift structures. If dikes break, temporary cofferdams will be constructed using steel sheet piles that have been stored for emergency use and utilized until the original dikes are repaired.[7, 8] There are several requirements for temporary cofferdams: Dikes to be constructed must be higher than the existing dikes; the structure must be stable at the estimated high-water level at which no overflow occurs; and at the ordinary water level, the structure must remain stable when earthquakes occur. Such performance was verified through seepage flow analysis and static and dynamic centrifuge model tests, and the design method was established.[9]

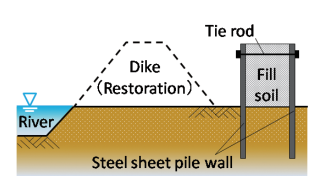
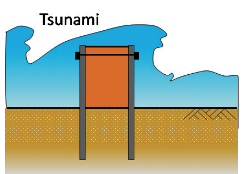
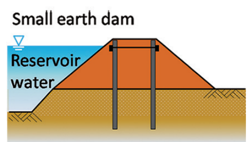
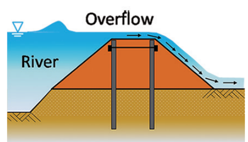
The seismic resistance of dikes reinforced with SPWs was verified for coastal and river dikes[10] (**Fig. 2**).[11] It has been demonstrated mainly in a shaking table model experiment that even when the side of a dike body collapses due to an earthquake involving liquefaction, the two-row steel sheet pile walls and tie rods suppress deformation of the core section and the crown height is retained by the steel sheet pile walls placed into the supporting soil. This aseismic mechanism was reproduced by finite element analysis that could consider liquefaction and the aseismic design for level 2 seismic earthquake was established. Recently, SPWs were applied to small earth dams and it has been demonstrated that SPWs are effective against dike body liquefaction caused by stored water getting into the dike bodies.[6]

Researchers have been working to verify the performance (resistance) to flood damage. Considering the damage by the tsunamis caused by the Great East Japan Earthquake, Mitobe, et al.[12] conducted a hydraulic model experiment assuming overflows of tsunamis over coastal dikes reinforced with SPWs. The experiment showed that even when the slope face on the land side is scoured, the crown height is retained, demonstrating SPWs' resiliency capacity. In addition, when the Great East Japan Earthquake occurred, SPWs were in use in Iwate as temporary cofferdams. It was reported that although they had been hit by tsunamis of possibly nine meters high, which greatly exceeded the crown height, at right angles, they remained without collapsing.[13] **Photo 1** shows an example of the constructed coastal dikes.[14]

The characteristics of SPWs that were demonstratively clarified through the series of technological developments mentioned above are listed below.

- When flooding occurs, steel sheet pile walls are already embedded into the ground work to suppress boiling. Even if an overflow occurs, the crown height is retained and thereby the volume of the overflow can be limited.
- When an earthquake occurs, the constraint effect of two-row steel sheet piles joined with tie rods suppresses deformation of the core section, mitigating the damage by liquefaction.
- As measures against complex disasters where tsunamis occur immediately after earthquakes, placing the bottom of steel sheet piles into the strong ground allows the crown height to be maintained during earthquakes and thereby overflows of tsunamis occurring later can be limited.

Table 1 Double steel sheet pile walls employed on the various types of dikes

	Temporary cofferdam using double steel sheet pile wall	Coastal dike	Small earth dam	River dike
				
Design manual	○[2]	○[3]	○[4]	○[5]
Earthquake protection	○	○	○	○
Water damage protection	Estimated high-water level (without overflow)	Tsunami protection	Against heavy rain (under development)[6]	Against heavy rain with overflow (under development)

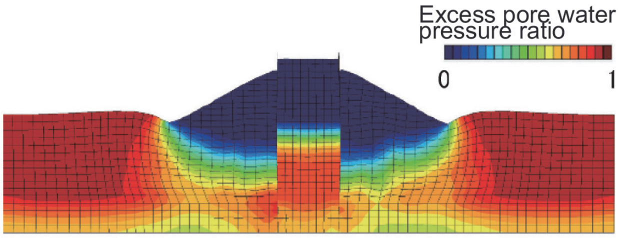


Fig. 2 Verification of reinforcement effect for river dikes with double steel sheet pile wall using seismic analysis[11]

(a) Double steel sheet pile walls constructed using Press-in Method

(b) Double steel sheet pile walls connected by tie rods

Photo 1 Construction example of double steel sheet pile wall[14]

3. Demonstration of Resilience Capacity against Long-time Overflows in a Laboratory Experiment

River dikes reinforced with SPWs were adopted as a self-supporting core wall in the development of evaluation technologies that contribute to reinforcing the structure of river dikes against overflows, which was publicly offered research at the request of National Institute for Land and Infrastructure Management in FY2021.[15] Nippon Steel has been promoting their research and development with the Tokyo Institute of Technology and Kyoto University. A point of difference from the aforementioned coastal dikes that may be struck by tsunamis is the duration. For example, in the experiment by Mitobe, et al.,[12] the assumed duration of tsunamis was ten minutes according to actual size conversion (overflow depth of 2 to 5 m) while the overflow duration for river dikes is three hours (overflow depth of 30 cm) as an index.[16]

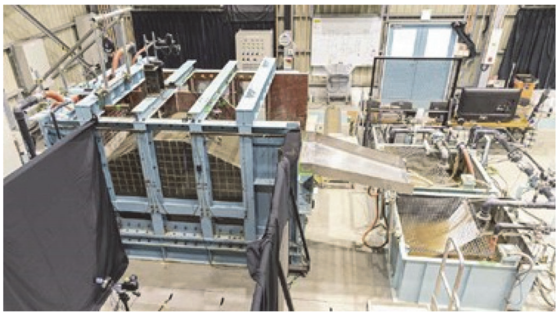


Photo 2 Hydraulic laboratory equipment with earth tank

Table 2 Sheet pile specification employed in the experiment cases

Case	Sheet pile length L (mm)	Embedded depth from ground level EL (mm)	Sheet pile thickness t (mm)
EL 1 000	1 400	1 000	6.0
EL 500	900	500	
EL 300	700	300	
EL 100	500	100	

Nippon Steel introduced new circulating-type water supply and drainage laboratory equipment that can cause an overflow for a long period of time into the RE Center (Futtsu City, Chiba) (**Photo 2**). The equipment was used to perform a hydraulic laboratory experiment using an embankment model. For the 1/15-scale model, the dike height and crown width were 400 mm (assumed actual size dike height and crown width of 6 m); the dike was reinforced with SPWs (equivalent to actual size hat-type steel sheet pile 25 H). This section describes cases in which the depth of steel sheet piles embedded into the ground was used as a parameter (**Table 2**). The depth of 1 000 mm in the EL 1 000 case is sufficiently long. The depth of 500 mm in the EL 500 case is the standard depth when the dike receives water pressure equivalent to the dike body height based on experience.[9] The depths of 300 and 100 mm in the EL 300 and EL 100 cases are shorter than that.

The overflow water depth was set to 20 mm (life-size overflow depth of 30 cm) according to the aforementioned index. For details of the experimental procedure, refer to that in the research by Mochida, et al.[17]

In the experiment, the slope face on the land side was completely eroded by an overflow in all cases; after the scouring advanced to the basement layer under the ground surface, the situation settled when the scouring depth was approximately 100 mm, turning to a stable state. **Photo 3** shows the sides of the dikes after an overflow continued for 50 minutes (equivalent to three hours in the actual size). In the EL 1 000 and EL 500 cases, the steel sheet piles have not tilted. Meanwhile in the EL 300 case, they have slightly tilted and in the EL 100 case, they have significantly tilted.

Figure 3 shows the bending moment distribution in each case. The depth and bending moment are values converted to the actual size. In the EL 1 000 and EL 500 cases, the positive bending moment (active earth pressure working from the core to the land side) occurred on the steel sheet piles on the land side above the ground surfaces; and the negative bending moment (passive earth pressure working from below the ground surface on the land side to the core

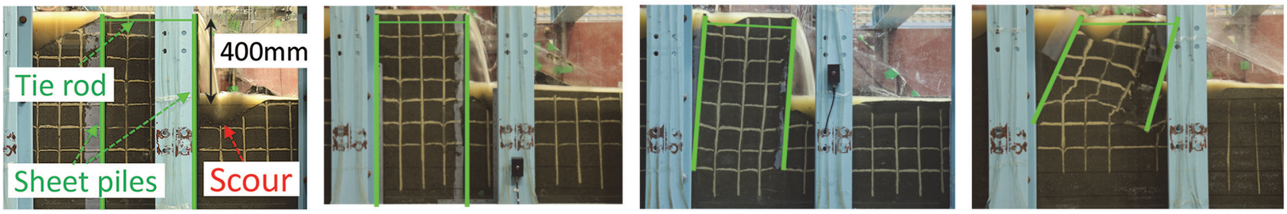


Photo 3 Overflow laboratory experiment for river dike reinforced with double steel sheet pile wall

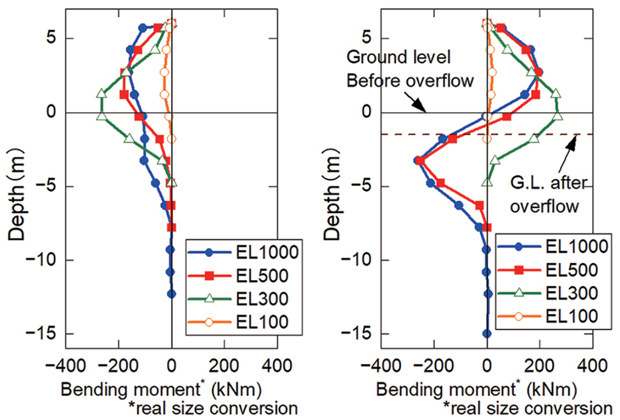


Fig. 3 Bending moment of sheet piles in the final state of overflow

side) occurred below the ground surfaces so as to resist the positive moment. In the EL 300 case, no negative bending moment occurred on the steel sheet piles on the land side while the moment peak on the river side was large. This suggests that the steel sheet piles on the land side may have been supported by the steel sheet piles on the river side via the tie rods. In the EL 100 case, the bending moment was small, which indicates that the walls rarely worked as resisting members.

Moreover, in the EL 100 case, the measured overflow volume was more than the supplied volume, which means that the crown height lowered and the river water flowed. In the other cases, the overflow volumes were equal to the supplied volumes, which means the initial crown height was retained. The results above show that for dikes reinforced with SPWs, even when the slope faces on the land side are eroded and the earth below the ground surface is scoured, the crown height is retained if the embedded depth is appropriate and thus the walls can resiliently withstand a long-time overflow.

4. Conclusion

To reduce flood damage, which frequently occurs in Japan, we have been researching and developing SPWs as river dikes having resiliency capacity. This paper introduced mainly the SPWs' resilience capacity against long-time overflows. To put SPWs into practical use, we will retain the SPWs' seismic resistance, and workability, etc. that have already been established; propose new design methods based on the relationship between the SPWs' resistance mechanism and overflows/scouring; and upgrade the durability, the ease of maintenance and management, and other requirements demanded for river dikes, contributing to disaster prevention and mitigation in Japan.

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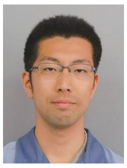
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