Challenge to clarify effectiveness and failure mode of levees reinforced with steel sheet piles against overtopping and scouring

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ABSTRACT

In recent years, the number of river levee failures in Japan has been increasing. Most of the failures are caused by overtopping. In response, there is a need to adopt adequate measures to retain river water while allowing overtopping with a high degree of redundancy. A levee reinforcement method by creating a self-supporting core wall in the center of the levee has been proposed. In this study, the core wall is formed by sandwiching the levee core using steel sheet piles. Therefore, experimental equipment was designed and installed that can semi-permanently reproduce "seepage flow through the underside of the steel sheet pile" and overflow, and can observe the behavior in the ground. By using this equipment, physical model tests on 1/15-scale models are performed to examine the resistance mechanism of the core wall against overtopping, considering the scouring on the back side of the river levees. The test results showed that the core wall can be made stable even under conditions where seepage flow and scouring occur, by ensuring a sufficient embedment depth of the sheet pile wall.

Key words: *Overtopping, Steel sheet pile, scouring, River levee, Seepage flow*

1. Introduction

Recently, severe failures due to heavy rains have increased in Japan, particularly the considerable damage caused by flooding. Thus, effective and rational countermeasures are required to maintain the height of river levee without collapse, even under overtopping. To achieve these goals, we considered implementing a freestanding structure integrated into the levee and ground to resist various forces. In this study, we propose installing double-steel sheet pile walls in levees, as shown in Fig.1.

Double-steel sheet pile walls are used as temporary barriers when river levees are excavated during rainy seasons. Most studies on overtopping have focused on tsunamis in coastal levees, and only a few studies have been conducted on the freestanding structures to reinforce levees against overtopping.[1)2)3)4)] Therefore, the changes in pore water pressure in river levees due to overtopping, the quantitative relationship between the amount of scour and deformation of steel sheet piles, and the critical conditions of levees reinforced with double-steel sheet pile walls during overtopping and scour have not been clarified.

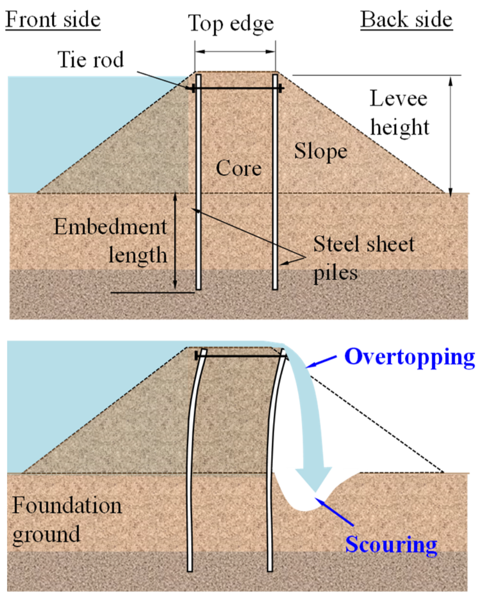


Figure 1 A levee reinforced with double-sheet pile walls

Thus, the proposed method is required to clarify the influence of scouring on the back side of double-steel sheet pile walls, as shown in Fig.1, during and after overtopping. Therefore, we conducted an experimental study to verify the effectiveness and behavior of double-steel sheet pile walls using a 1/15 scale model. The following overtopping conditions were required: to maintain the river levee height at 30 cm and to continue it for 3 h to verify these phenomena[5)].

2. Methodology

The experimental equipment shown in Fig.2 was designed and installed to investigate the behavior of a levee reinforced with double-steel sheet pile walls during overtopping. Regarding the overtopping conditions, the equipment was designed as a recirculation type to ensure that the target overtopping depth could be modeled over a long period. Regarding the scale, the depth of the ground was designed such that the embedment length could be appropriately set to achieve both the "seepage flow under the sheet pile" and "length required for stability". Accordingly, the behavior of double-steel sheet pile walls and the resistance mechanisms for different embedment lengths during overtopping were investigated.

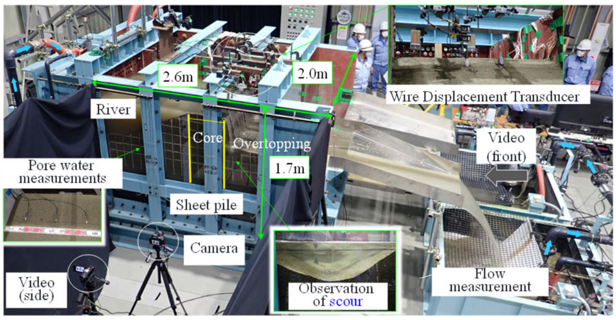


Figure 2 Overview of the installed experimental equipment

The prototype levee with a height of 6 m and a crown width of 6 m was modeled with a geometric scale factor of λ = 1/15. The bottom surface of the soil tank was set to the reference level (height = 0 mm). The thickness of the foundation ground was 1000 mm and the height of the levee body was 400 mm. For smooth observation of the instability of the levee owing to overtopping-induced scouring on the back side, sandy soil, which is prone to erosion and whose properties are summarized in Table 1, was used to construct the model. During the tests, the discharge rate, pore water pressure in the ground, displacement and strain of the steel sheet piles, and axial force of the tie rods were measured. All the readings were set to zero before the water began to rise (t = 0). To visualize the displacement of the model embankment through the transparent windows, 100 mm × 100 mm grids made of white sand were placed between the model and observation windows. The steel sheet piles were made of 6-mm-thick steel plates (SS400) installed at the shoulders of the levee. Hereafter, the core sandwiched between the sheet piles was called the core wall. The tops of the steel sheet piles were connected using five-tie rods (steel bars). The diameter of the tie rods was 6 mm, and the tie rods were connected to steel sheet piles at a depth of 10 mm from the crest of the levee under a hinged condition.

Table 2 shows the overtopping conditions. An overflow depth of approximately 20 mm was maintained for 3 h. This corresponded to an actual overflow depth of 33 cm for approximately 12 h in the prototype scale, if the scaling laws based on Froude's law were followed. Since the stream gradient of rivers in Japan are relatively large, the Ministry of Land, Infrastructure, Transport and Tourism in Japan (2022) expected the reinforced levee not to be breached with the overtopping whose overflow depth was 30 cm for 3 h period[5)]. According to this, we set the overtopping conditions, if the reinforced levee performed well during the overtopping condition, we could conclude that the reinforced levee showed the expected minimum performance of the reinforced levee.

Table 1 The properties of a soil

Parameter	Value
Angle of shearing resistance, φ'	38.5 [°]
Cohesion, c'	1.4 [kPa]
Hydraulic conductivity, k	2.2×10^{-4} [m/s]
Mean particle size, D_{50}	0.5 [mm]
Water content ratio ω	16 [%]
Bulk density, γ	17.4 [kN/m^3]
Degree of compaction, Dc	90 [%]

Table 3 summarizes the test cases. N-Y represents the case without reinforcement. The embedment length of the steel sheet piles was longest in EL1000, and the tips of the sheet piles were connected to the base of the soil tank in a hinged condition. In this case, to allow water to seep from the river side to the back side in the foundation ground, seven equally spaced holes with a diameter of 18 mm were made near the tip of the sheet piles. To examine the effects of the embedment length of the sheet piles on the failure modes of the core wall, cases with different embedment lengths of the sheet piles (EL300) were also considered.

Table 2 Overflow conditions

Model scale			Prototype scale	
Overflow depth [mm]	Water supply flow rate [ℓ/min]	Period [hr]	Overflow depth [mm]	Period [hr]
22	270	3	330	11.6

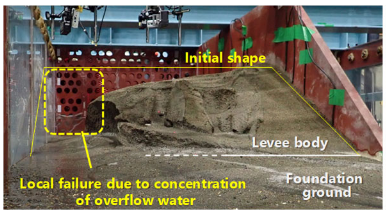
Table 3 Test cases

Case ID	Condition	Embedment length
N-Y	No reinforcement	-
EL300	Smaller embedment length	300 [mm]
EL1000	Semi-infinite embedment length	1000 [mm]

3. Results

Figure 3 shows the overtopping-induced failure process of the levee without reinforcement (N-Y). The erosion of the levee started from the shoulder of the slope on the back side, and the levee crest was lost approximately 30 s after the overtopping began. The levee was breached 2 min after the overtopping began. Figure 3 (b) shows the state of the levee from the back side after the experiment. The erosion was not uniform in the longitudinal direction, and the concentration of the flow resulted in local failure.

(a) 1 min from start of overtopping

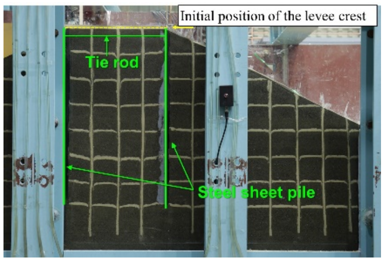


(b) Final state of levee from back side[6)]

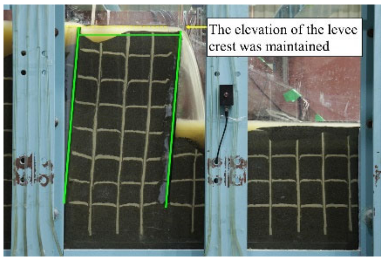
Figure 3 Breaching of the levee without reinforcement (N-Y)

Double-steel sheet pile walls reinforcement effect and behavior during overtopping were experimentally investigated, considering the length of embedment (Le) as a parameter. The results of this study also reported the short (Le = 0.3 m) and long (Le = 1.0 mm) Le conditions.

Figure 4 shows the damage process of the levee in EL300, when the slope on the back side is lost and the scouring depth occurs. From (a) to (b), in response to the scour, horizontal displacement occurred, although crest was maintained.



(a) start of overtopping



(b) t = 3 hrs

Figure 4 The damage process of reinforced levee (EL300)

Figure 5 shows the damage process of the levee in EL1000 at the start of overtopping, when the slope on the back side is lost, and when the scouring depth on the back side reaches a steady state. From start to steady state, no considerable deformation occurred in the core wall, the elevation of the levee crest was maintained, and the slope on the back side was lost.

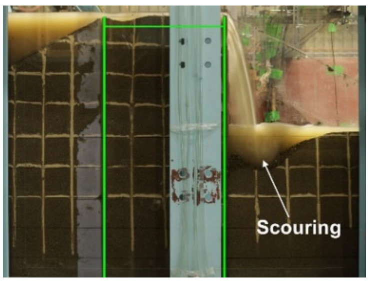


Figure 5 The damage process of reinforced levee (EL1000_t = 3 hrs)

Figure 6 shows the deformation process of the double-steel sheet pile walls during overtopping. Under the short Le conditions, the horizontal displacement (Dh) reached approximately 15 mm at the target time and gradually increased because of overtopping and scouring, whereas the levee height remained constant. In contrast, under the long-Le conditions, Dh was suppressed to approximately 5 mm at the target time, after which the displacement converged.

Before overtopping, seepage occurs in the rising water level, flowing from the bottom of the sheet pile to the core (①). Afterward, overtopping erodes the slope (②). PWP converges after water seeps into the core from the top edge (③). The scouring progresses gradually and converges (④). The displacement occurred gradually from immediately after water overtopping until scouring steady (④).

The bending moments in the double-steel sheet pile walls are shown in Figure 7; no yielding was observed under either condition. However, under the long-Le condition, the moment distribution was reversed, indicating that the ground reaction forces acted on the sheet piles. These results highlight the importance of ensuring a sufficient Le on the back side of the levee to enhance overtopping resistance of double-steel sheet pile walls, considering scouring.

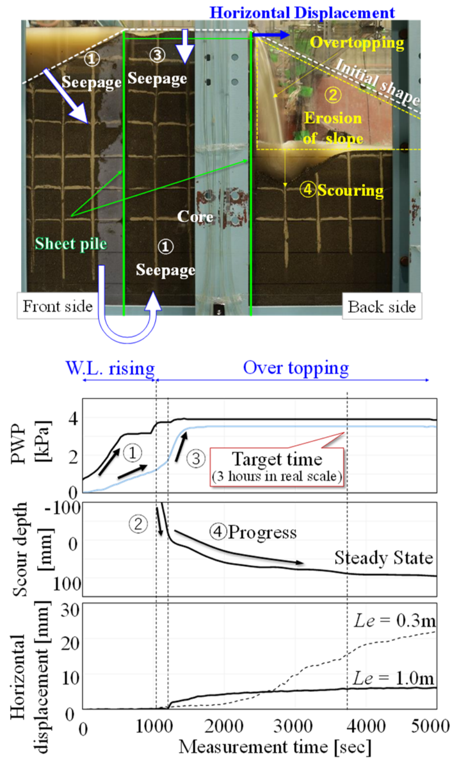


Figure 6 Deformation state at target time and changes in measured values (*Le* = 1.0m)

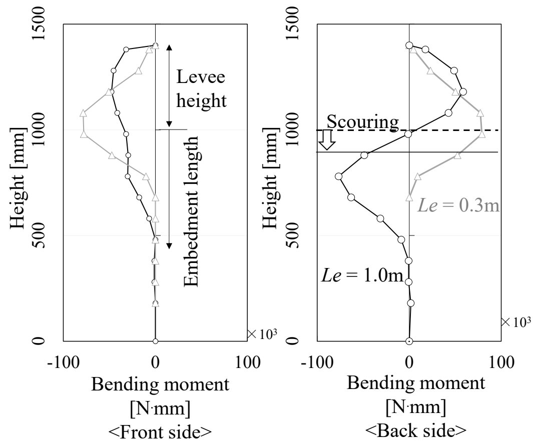


Figure 7 Bending moment at the target time

Figure 8 and Figure 9 show the distributions of the subgrade reaction (second derivative of the bending moment distribution) at 3700 s in Step 1. Based on the EL1000 results, a schematic of the forces acting on the steel sheet piles is shown in Figure 9. The red arrows indicate the resistance to deformation of the steel sheet pile, and the blue arrows indicate the forces causing sheet pile deformation. In EL300, since the embedment length of the sheet pile is small, the reaction ⑤ is not mobilized.

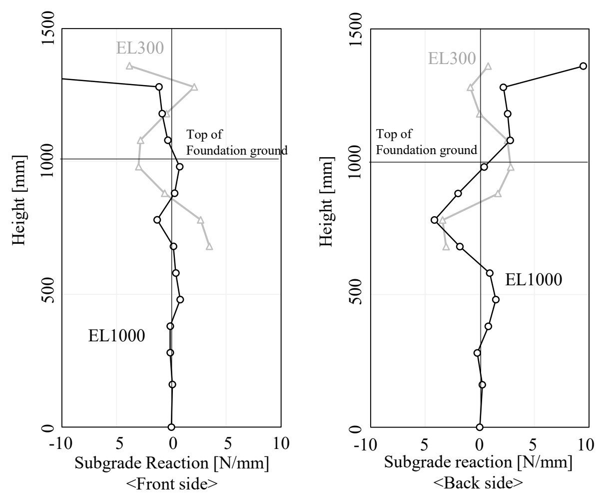


Figure 8 Distribution of subgrade reaction on the river side sheet pile (at t = 3700 s, Step 1)

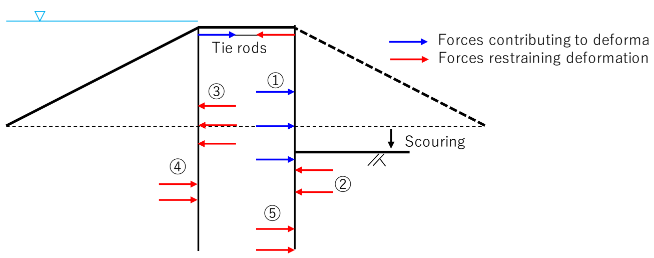


Figure 9 Forces acting on steel sheet piles [6)]

4. Conclusion

Through the devised experiment, this study clarified the effectiveness and behavior of levees reinforced with double-steel sheet pile walls against overflow. First, we designed experimental equipment to simulate long-term overtopping and implemented an embedded structure as a countermeasure. Subsequently, we verified the structural performance of double-steel sheet pile walls against overtopping by conducting experiments with the embedded length as a parameter using this experimental facility. As a result, the highly effective performance of double-steel sheet pile walls against overtopping was demonstrated, as they managed to maintain the required embedded length while considering the scouring phenomenon on the back side of the double-steel sheet pile walls. The following two characteristics were observed to change over time during overtopping: [1] gradual progression of the deformation with the development of scouring and [2] gradual increase in the deformation owing to scouring for double-steel sheet pile walls with sufficient Le; however, the deformation eventually converged if the overtopping water depth was kept constant.

5. Further work

Implement numerical simulations to validate and expand upon the experimental results. This would include varying parameters such as soil type, water flow rates, and different configurations of steel sheet pile walls, to gain a more comprehensive understanding of their behavior under various conditions.

In particular, the effect of the width of double-steel sheet pile walls on structural stability and acting earth pressure is not clear, and research will focus on this point.

And, the river levee has a long structure along the river. Thus, to apply double-steel sheet pile walls under these conditions, ensuring stability is necessary, even if the structure and ground conditions change along the longitudinal direction. In the future, numerical analysis will address this issue .

Additionally, the following suggestions could be considered:

Conduct long-term field studies to observe the performance of steel sheet pile walls in actual levee systems. This would provide valuable data on the durability and effectiveness of the reinforcement method over extended periods.

Acknowledgments

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