Investigation into the performance of levees and embankments reinforced with sheet pile walls

N. J. Koffi
Researcher, Scientific Research Section, GIKEN LTD., Kochi, Japan
H. H. Tamboura
Chief, Scientific Research Section, GIKEN LTD., Kochi, Japan
Y. Ishihara
Manager, Scientific Research Section, GIKEN LTD., Kochi, Japan
K. Toda
Chief, Scientific Research Section, GIKEN LTD., Kochi, Japan
Y. Toda
Researcher, Scientific Research Section, GIKEN LTD., Kochi, Japan

ABSTRACT

Levees and banks are vital defenses against water-related natural disasters. Recently, intense rainfall events or tsunamis have demonstrated the vulnerabilities of traditional earthen levees, whereas gravitational-type levees have collapsed under the hydrodynamic effect of tsunamis. This situation has incited the need for the development of disaster-resilient structures, leading to the consideration of levees and banks reinforced with single/double-sheet pile wall structures (Implant™ Structures). Despite the potential advantages and benefits of the Implant™ Structures, the adoption of these innovative coastal protection solutions is in its infancy. This hesitancy could be attributed, to a lack of awareness regarding their advantages, a shortage of practical application examples, and a lack of technical advantages. This research investigates the effectiveness of double-sheet pile walls with or without partition walls to upgrade coastal levees and bank protection. Based on an extensive literature survey, this study summarizes (1) the proven advantages and (2) the benefits of the existing application of the levees equipped with the double-sheet pile wall. The possible benefits were identified to improve the overall stability, erosive resistance, and disaster prevention capabilities of the earthen levees. Furthermore, the applications were found in the published literature including the levees on the Kochi Coast, a reservoir in Kochi Prefecture, the river banks in the UK, the USA, and Germany, and some others. The new insights gained from this investigation are expected to promote the advancement of implementation levees equipped with double-sheet pile walls, thus addressing critical issues in the field of water-related disaster management.

Keywords: *Levee Reinforcement, Double Sheet Pile Walls, Coastal Protection, Disaster Management.*

1. Introduction

1.1. Statement of the conventional levee issues

Japan is a 70% mountainous country, and most of its population, assets, infrastructures, and industries are concentrated in the sensitive coastal area, which has always been prone to frequent typhoons, seismic activities, and tsunamis (Mimura et al., 2011). Storm surges from typhoons, to earthquake-triggered tsunamis recently in the areas of interest, have made it rough socio-economic disasters, and they have rendered Japan's coastal communities extremely vulnerable. In March 2011, Japan experienced a combined M9.0 earthquake and a giant tsunami, which was unprecedented in its history. Subsequently, this historical earthquake-induced tsunami generated waves reaching heights of 10 meters or more and a maximum run-up height of 40 meters (Hirose, 2022). Subsequently, this gigantic seismic event coupled with the tsunami, several damages, and the collapse of numerous coastal levees, embankments, and infrastructure were recorded. In May 2011, the number of fatalities and missing people topped 24,000 (Mimura et al., 2011). **Fig. 1** depicts a view of the extent of damage and destruction caused by the earthquake-triggered tsunami on protective coastal levees along the coastal area of Japan (Hara et al., 2012).

Another example water-related disaster was recorded in the Kanto region in Japan, where a heavy rainfall-induced typhoon (Hagibis Typhoon), occurred in 2019. The Hagibis Typhoon was large and fierce causing record-breaking rainfall events over a wide area in Japan, thus resulting in extensive water-related damages in many areas (Yokoki et al., 2022). As a result of the record-breaking heavy rainfalls, levees were breached at 140 locations on 71 rivers in 20 river basins, including 12 locations on 7 rivers in 6 river systems managed by the national government, thus causing large-scale flood damage, underscoring the vulnerability of Japan's levee infrastructure to such natural water-related disasters.

1.2. Objectives of this review paper

Conventional levees in Japan are usually made of earthen embankments, which were proven to be insufficient to resist rising waters during natural disasters, including severe typhoon-induced storm surges, heavy rainfall, flooding, and earthquake-triggered tsunamis (**Fig. 1**). These catastrophic events motivated the urgent need to enhance existing countermeasures due to Japan's high vulnerability against such water-related disasters, highlighting the importance of upgrading and fortifying levee defenses. To date, the Implant Lock Levee technology, integrating steel sheet pile walls to earth to

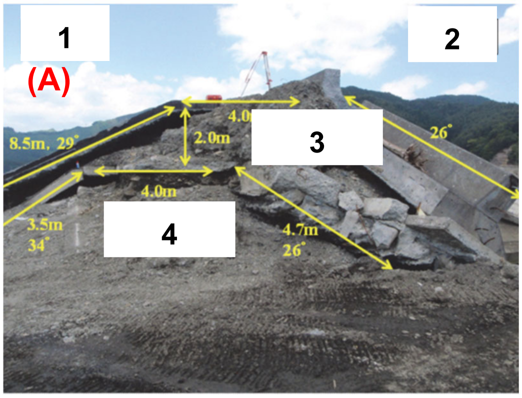

Fig. 1. Structure of the levee body at the Otsuchi River levee break point) during the 2011 tsunami in Japan (Hara et al., 2012). Land side [**1**], River side [**2**], Raised part [**3**], Old embankment [**4**].

strengthen the structure of the earthen levee, emerged as a possible resilient solution against tsunamis and floods. Recent studies and field observations support the effectiveness of this technical approach, making the earthen levees with sheet pile walls robust and resilient against huge earthquake-induced tsunamis and serious floods, resulting from extreme rainfall events. Subsequently, wide research has focused on the earthen levees with double-sheet pile walls, including computational modeling, laboratory-scales experimental models, and real-scale in-situ research conducted by various researchers (Takuma, 2019). However, a comprehensive review analyzing the benefit of adopting the Implant™ Structures to reinforce the traditional levees is missing. Here, the focus of this review is to investigate deeper into the structural benefits of levees with sheet pile walls including a particular focus on their effectiveness in mitigating the effects of earthquakes and extreme water-related disasters. In addition, this review study emphasizes the advantages and practical applications of levees with sheet pile walls, aiming to promote their adoption in Japan and worldwide coastal, and riverine areas to enhance disaster resiliency and safety of the communities.

2. Review of the performances of the existing coastal protections

A typical levee is an engineered structure designed to lower the chance of an area getting flooded by preventing floodwaters from entering the protected zone (which can be along rivers or coastlines). Levees are usually made of earth, either in a uniform way (homogenous levee) or with different zones (zoned levee), sometimes supported by a concrete structure (known as a concrete-covered levee). Despite their widespread use, conventional concrete-reinforced earthen levees have demonstrated vulnerabilities during intense natural disasters, such as serious floods due to extreme rainfall events or tsunamigenic earthquakes. Notable failure mechanisms have been observed such as (a) earthquake-induced tsunami causing an overtopped flow of water over the embankment, (b) wave erosion on the waterside reducing the cross-section thickness and weakening embankment, (c) uncontrolled seepage erosion of the soil from the embankment or its foundation, (d) liquefaction of the foundation soil, and (d) scouring at landward and seaward toes caused by high water flow velocity. Similarly, gravity-based coastal protection made of heavily engineered superstructures suffered similar complete or partial destruction during the earthquake-induced tsunami events reported, due to the sliding failure at the soil-structure interface (Ishihara et al., 2018). These failures of the existing concrete-based levee and gravitational coastal protections contribute to the urgent need for innovative solutions that can enhance the resilience of future coastal protection systems.

3. Examining a potential solution: Justifying the double sheet pile approach

The occurrences of typhoon-induced storm surges or recent tsunami events triggered by earthquakes have underscored the imperative for enhancing existing countermeasures and their designs to effectively endure the unprecedented magnitude of such extreme catastrophes in specific regions. This necessity arises due to Japan's status as one of the world's most significantly exposed countries to such natural disasters. The lessons drawn from recent events emphasize the urgency of refining and fortifying these defensive measures, recognizing that certain areas may face unexpected and exceptionally severe tsunami events for example. Hence, there's a critical need to bolster the resilience of coastal protection systems, acknowledging the heightened vulnerability of Japan to these catastrophic occurrences.

During a post-earthquake tsunami event, significant contrasting effects were observed: while surrounding infrastructures suffered severe damage, a temporary cofferdam structure employing a double steel sheet pile wall in Iwate prefecture demonstrated resilience in the same vicinity, juxtaposed against the visibly ruined residential and commercial district adjacent to it (Takuma, 2019). This disparity is exemplified in **Fig. 2**.

Fig. 2. The resilience of the double-sheet pile cofferdam following the impact of a 9-meter tsunami in Japan's Iwate Prefecture in 2011(Otsushi et al., 2016).

Despite facing post-earthquake tsunamis estimated at 9 meters in height, surpassing the structure's crest perpendicular to the tsunami's trajectory, the steel sheet pile wall structure maintained both its functional operability and structural integrity (**Fig. 2**). Although ground scouring and soil drainage in front of the steel sheet piles due to the tsunami are expected, both the steel sheet pile walls and connecting tie beams exhibited enduring stability. The key factor contributing to the structure's remarkable resilience against substantial vertical and lateral forces was the anchorage of the sheet piles, complemented by the interconnection of double-sheet pile walls through inner bulkhead walls and tie-rods (Otsushi et al., 2016).

Over ten years before the 2011 earthquake occurred, GIKEN LTD. advocated for implementing the levee with sheet pile walls (Implant Lock Levee) to protect levees rather than solely relying on conventional levee structures (**Fig. 3**). The Implant Lock Levee structure constructed by the press-in technology consists of piles (tubular or sheet piles) that are pressed into the ground where they are securely supported by the earth. The Implant Lock Levee protection carries both horizontal and vertical loads, using the "size of section" and "depth of penetration into the subsoil". As a result, the Implant^{TM} Structures exhibits high strength as an aggregate having individual structural components that are supported by the ground (integrated into the ground). Therefore, it is highly resistant to ground displacement caused by the motion of earthquakes, tsunamis, and other external forces, serving as a “resilient” disaster-prevention infrastructure (Giken LTD., 2024). A major feature of this levee structure is the fact that it is designed to withstand failure in the event of a large earthquake, in addition to withstanding the effects of overtopping and seepage.

However, it was difficult for civil engineers to adopt the Implant Levee technology until the earthquake and tsunami happened to prove the fragility of conventional levees and the high resilience ability of Implant™

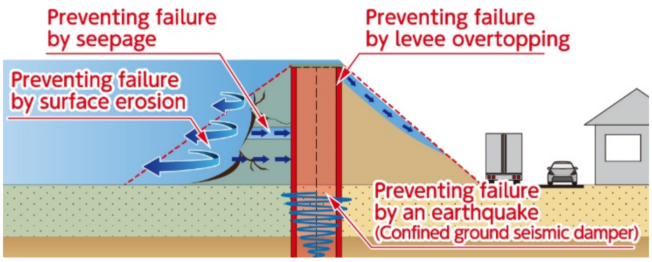

Fig. 3. Illustration of the Implant Lock Levee preventing failures by maintaining the structural function. (https://www.giken.com/en/solutions/implant_lock_levee/).

Structures. Thus, in 2012, Implant Levees (levees upgraded with sheet pile walls) started to be adopted as national countermeasures against failures (seepage, surface erosion, overtopping, subsoil liquefaction) (Ishihara et al., 2020). Following this, there has been a significant emphasis on enhancing earthen levees by incorporating double-sheet pile walls.

4. Advantages of double sheet pile walls

4.1. Resiliency against structural deformation and soil foundation liquefaction

The concept of integrating double-sheet pile walls in levee design was described as a promising alternative to strengthen conventional structures. To substantiate this concept, extensive research, primarily conducted in Japan, has encompassed numerical simulations and physical in-situ or laboratory-scale experiments, as outlined in **Table 1**. For example, Fujiwara et al., (2017) investigated the impact of levee reinforcement using scaled double-sheet piles with partition walls (1/25 scale). Three scenarios were examined: Case-A (no countermeasure), Case-B (double sheet piles), and Case-C (double sheet piles with partition walls). Shaking table experiments were conducted with seismic input derived from the 2011 Tohoku gigantic earthquake-induced tsunami. These experimental results demonstrated that the levee equipped with sheet piles (with partition walls) (Case-C) exhibited 10-15% less settlement compared to the one without countermeasures, confirming the resilience of reinforced levees in reducing deformation/settlement due to foundation liquefaction during the earthquake event, thus preventing structural collapse. Subsequently, the reproducibility of these findings was validated through computational experimental models (Fujiwara et al., 2017, 2018) yielding similar results indicating a reduction in liquefaction-induced settlement and a restriction of bending deformation in levees equipped with sheet piles. Moreover, the investigation revealed that sheet pile walls enhance soil conditions by restricting lateral soil displacement, fortifying resilience against liquefaction-related damage (Takuma, 2019), particularly with deeper embedment to reach the non-liquefiable ground layer to get more bearing forces from the subsoil. In contrast, Noda et al., (2009) illustrated that in the context of ground fortification using the sheet pile technique, if the tips of the sheet piles are situated within a densely-structured soft clayey layer, significant disturbance of the clay in that region may occur during earthquakes, particularly with elevated embankments and substantial embankment loading. This can result in notably increased settlement during and post-earthquake events.

4.2. Tsunami strike, overflow, erosion, seepage, and scouring resistance

Overflow is known to have caused failures of embankments during the 2011 Tohoku tsunami where the scour was identified as one of the main processes of the failure around the landward toes of the coastal embankments. Severe erosions were often observed at the landward toes, caused by water flow over the embankments due to tsunamis or storm surges, leading to significant scouring and the subsequent failure of concrete armors on landward slopes causing the complete flushing of the embankments (**Fig. 4**). Accordingly, extensive research has identified potential advantages of levees with double-sheet pile walls, including improved stability, enhanced erosive resistance, and increased disaster prevention capabilities against combined action of tsunami strikes, overflow, scouring, and erosion (**Table 1**). For example, Otsushi et al., (2016) and his teammate investigated the effect of tsunami overflow on the reinforced levee scaled at 1/50.

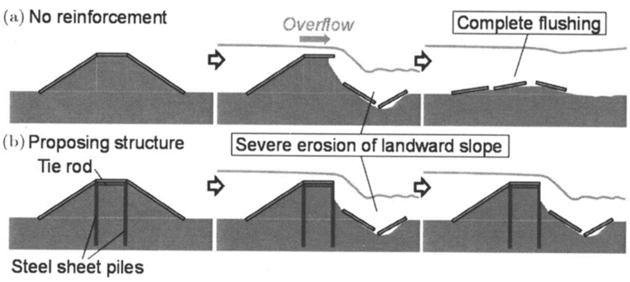

Fig. 4. (**a**) Mechanism of a main pattern of coastal embankment failures by the 2011 Tohoku Earthquake Tsunami and (**b**) the proposed upgraded structure with steel sheet piles (Mitobe et al., 2016).

The results revealed that sheet piles prevented the structure from collapsing under severe hydraulic conditions due to overflow water pressure that caused scouring in the interior ground area of the levee and allowed the structure to maintain a tenacious flood-proception function. Similarly, Mitobe et al., (2016) experimentally evaluated reinforcing embankments against tsunami overflow using steel sheet piles. They found that single and double-sheet pile walls largely maintained embankment height and cross-sectional area compared to the levee without sheet pile wall, where complete erosion occurred. Furthermore, they found that the development of scour behind the embankment led to reduced velocity compared to an embankment with no scour. This implies the scour contributes to some energy dissipation. Specifically, the velocities behind the sheet pile walls were lower than the no scour cases, indicating the scour reduced velocities and dissipated energy of the overtopped water. Moreover, the levees with double-sheet pile walls were found to minimize seepage, piping failure, and liquefaction of the soil foundation (**Table 1)**. The proposed embankment equipped with double steel sheet pile walls exhibited promising assets for resilience against extreme earthquake and tsunami events, as well as rapid reconstruction needs. Specifically, the embankments with double sheet pile walls demonstrated an ability to maintain functionality against overtopped water conditions that could fully erode an embankment without sheet pile walls. Additionally, various comparable numerical and laboratory scale studies have confirmed the effectiveness of reinforcing earthen levees with sheet pile walls to address failures resulting from earthquake-induced tsunamis, soil liquefaction, erosion, seepage, and overtopped water flow, as detailed in **Table 1**, highlighting the advantages of levees equipped with sheet pile walls. Although specific *in-situ,* laboratory-scale, and computational studies have demonstrated the effectiveness of levees equipped with double-sheet pile walls in mitigating the impact of seismic events and tsunamis (Otsushi et al., 2016; Fujiwara et al., 2017, 2018; Takuma, 2019), further analyses at a larger scale would further support the applicability of these construction technologies of levees with implanted sheet pile walls.

4.3. Application examples around the world

Around the world, the earthen levee with single/double sheet pile walls was adopted to prevent water-related disasters. For example, the Island Barn Reservoir in the United Kingdom was faced with leakage issues. As a countermeasure, large-scale remediation work was executed, where 386 sheet piles were installed over 230 m in length by the Press-in method, thus providing a nearly impermeable barrier steel sheet as cut-off walls (Rettura et al., 2018). This solution effectively intercepted the seepage paths, reducing seepage discharge and enhancing the structural stability of the embankment (**Fig. 5a**). Likewise in Germany, Geppert et al., (2021) addressed extensive flood damage along the River Elbe, utilizing the pressed-in sheet pile walls to reinforce dykes, showcasing the method's reliability, efficiency, and environmental sustainability. Moreover, the adaptability of this construction method reduced environmental impact, and the consistently high-quality, reliable, and proven upgraded levee/embankment with press-in technology persuaded decision-makers to include this reinforcement approach in German standards and technical literature (Geppert et al., 2021). Crossing the Atlantic to the United States of America, the study by Takuma et al., (2021) demonstrated the effective use of press-in piling with GRB System™ (GIKEN Reaction Base System) for noise- and vibration-free levee upgrading method in densely populated urban areas (**Fig 5b**).

Fig. 5. (**a**) Example of installation of cut-off sheet pile walls by the GIKEN press-in pile machine (Island Barn Reservoir, United Kingdom) (**b**) Example of repair and upgrade of riverine levees by 950 pairs of sheet piles (USA).

Furthermore, the application of sheet pile walls in the United States has successfully demonstrated the levee upgrading method, thus overcoming logistical and environmental challenges near homes and in limited working space. In Japan, concerns over a potential loss of functionality in coastal levees in Kochi due to liquefaction-induced settlement and anticipated ground subsidence due to the probable M9.0 earthquake, with a 70% probability of occurrence in the coming 30 years and the expected tsunami height in Kochi Coast of 15 – 25 m, led to a construction project starting in 2011 for seismic reinforcement (Ishihara et al., 2020). To address this upcoming issue, a project commenced in 2011 to reinforce the 13-kilometer-long levees for seismic and subsoil liquefaction resilience. Requirements of construction methods included tenacity, minimal environmental impact, and low construction cost and time. Thus, double sheet pile walls with the GIKEN press-in method were chosen for reinforcement in some coastline sections, such as the Nino section (1.6-kilometer-long). The decision-making process and subsequent results from the Nino coastline levee upgrade demonstrated satisfactory performance in meeting design, speed, and construction challenges while minimizing environmental impact (**Fig. 6**). It is anticipated that the completion of the remaining sections with double sheet pile walls will contribute to mitigating damages from the coming huge earthquake and tsunami along the Kochi Coast.

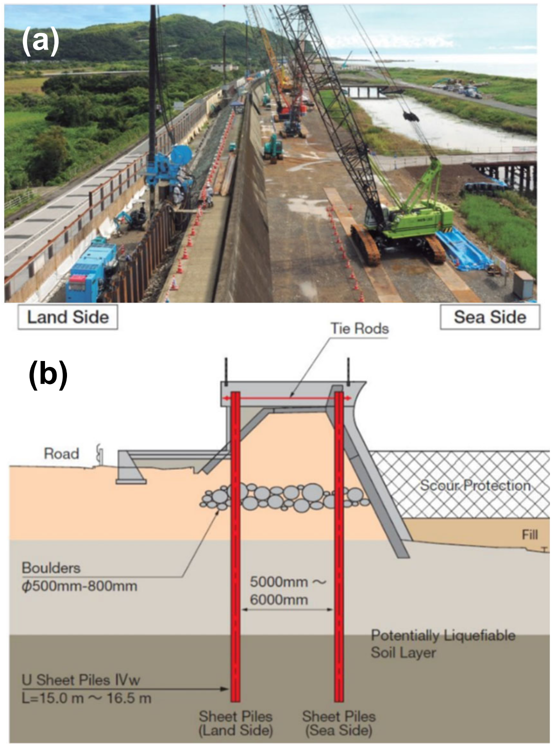

Fig. 6. (**a**) Upgrading process of the existing Coastal levee using the double sheet pile walls (Nino section, Kochi, Japan) (**b**) View of upgraded levee section of the coastline in Kochi, Japan.

These diverse and challenging global applications demonstrated the adaptability and reliability of integrating double-sheet pile walls into the existing levees, offering practical and cost-effective solutions to mitigate the impacts of water-related disasters (tsunamis and storm surges and levee subsoil liquefaction), as reported in the United Kingdom, Germany, Japan, and the United States of America.

4.4. Global perspectives on levees with sheet pile walls

Expanding the discussion to a global perspective unveils the significance of the levees constructed with sheet pile walls in the scope to mitigate structural vulnerabilities during the tsunamis triggered by earthquakes or other potential tidal waves resulting from typhoons or severe flooding due to extreme rainfall. While these structures have gained substantial attention in Japan, it is vital to assess whether comparable initiatives are being pursued in other regions worldwide facing similar water-related disasters.

Comparative analyses across the regions subject to earthquakes, tsunamis, or other extreme heavy rain and flood issues, could offer valuable insights into the effectiveness and the adaptability of the sheet pile-reinforced levees in diverse contexts. Understanding the experiences of the regions facing similar geological challenges allows for a comprehensive evaluation of the global applicability of this innovative approach. Exploring initiatives in countries such as those bordering the Pacific Ring of Fire or regions susceptible to tsunamigenic events could provide a broader perspective on the potential impact of the sheet pile-reinforced levees. Such insights contribute to the collective knowledge base, thus guiding further research and facilitating the exchange of the best practices in coastal protection. In this context, the global exploration of the sheet pile-reinforced levees goes beyond individual study cases, offering a holistic view that could update the ongoing efforts to enhance disaster resilience on a worldwide scale.

5. Conclusion

This research extensively explores the performances of the levees and embankments constructed with double sheet pile walls, focusing on their effectiveness in mitigating the devastating impacts of earthquakes, tsunamis other water-related disasters. The review elucidates the advantages of this innovative technology, emphasizing its resiliency against structural deformation, soil foundation liquefaction, storm surge, tsunami strikes, overtopped water, erosion, seepage, and scouring (**Table 1**). Key findings from various applications worldwide including the United Kingdom, Germany, The United States of America, and Japan illustrate the adaptability and the reliability of the double sheet pile walls in diverse settings. The Kochi coastline anti-earthquake/tsunami reinforcement project in Japan, the Island Barn reservoir reinforcement project in the UK, River Elbe in reinforcement embankment in Germany, and the U.S.'s Levee upgrading demonstrate successful implementations, addressing logistical challenges and showcasing the efficiency and the environmental sustainability of this innovative construction method. Despite the promising benefits, challenges such as cost considerations, construction complexities, and potential environmental impacts remain, necessitating further research and refinement. The significance of the ongoing research initiatives is underscored, as they strive to address these challenges to contribute to the widespread adoption of earthen levees/embankments equipped with sheet pile walls. The potential impact on disaster management and the resilience of the coastal protection system is highlighted, emphasizing the imperative to continue the exploration and the implementation of this earthen levee technology constructed with the implanted sheet pile walls to enhance global preparedness against water-related natural disasters.

Table 1 (*Continued on the next page*)**:** Summary of the existing studies describing the attribute of the coastal protection equipped with the Implant Structures. (○) denote the type of investigation, and the parameters studied or investigated in their studies. (-) denotes the type of investigations and parameters not included in their studies.

Infrastructure/Countermeasure	**Type of Experiments**			**Investigated parameters**							**Conclusions/ advantages**
	***in-situ* real large-scale**	**Numerical model**	**Lab-scale model**	**Settlement-resistance and deformations**	**Earthquake-resistance**	**Tsunami-resistance**	**Overtopping flow - scouring resistance**	**Soil-liquefaction resistance**	**Seepage-reduction**	**Overall resistance/stability of the upgraded levee**	
Levee reinforcement with double sheet-pile walls (Mitobe et al., 2016)	-	○	○	-	○	○	○	-	-	○	The embankment was successfully upgraded with double sheet pile walls to protect against tsunami overflow.
Levee and double sheet piles with partition walls (Fujiwara et al., 2018)	-	○	○	○	○	○	○	○	-	-	The increase in the interval of the partition walls increases the settlement of the coastal dyke increased and the bending of the sheet pile walls. However, the excess pore water pressure of the ground enclosed by double sheet pile walls and partition walls decreased. Earthquake-liquefaction resilient structure.
Levee reinforcement with double sheet pile walls with partition walls (Fujiwara et al., 2017)	-	○	○	-	○	○	○	-	-	○	Deformation/settlement reduction effect of the upgraded levees during an earthquake. Settlement increases with the increase of the interval of a partition walls.
Coastal dyke reinforcement with double sheet pile walls with partition walls (Otsushi et al., 2016)	○	○	○	○	○	○	○	○	-	○	Disaster-resilient method against tsunami, earthquakes, flood water overtopping, and soil liquefaction.
Coastal dyke + double sheet pile walls with partition walls (Takuma, 2019)	○	○	○	○	○	○	○	○	-	○	Disaster-resilient method against tsunamis, earthquakes, flood water overtopping, and soil liquefaction.
Embankment reinforcement with a double sheet-pile walls (Mitobe et al., 2014b)	-	○	○	○	-	○	○	○	○	○	Embankment reinforcement with steel sheet pile walls resulting in efficient countermeasures against tsunami overflow.
Embankment reinforcement with a single sheet-pile wall (Rettura et al., 2018)	○	-	-	-	-	-	-	-	○	○	Seepage and leakage issues in the embankment were remediated by implanting an impermeable cut-off sheet pile wall from the crest.
Cofferdam reinforcement with a double sheet-pile walls (Jiang et al., 2023)	-	-	○	-	-	○	○	-	○	○	Achieving both safety and overturning stabilities. High seepage resistance; highly resistant against hydrodynamic pressure due to extreme surge storms or tsunamis.

Table 1 (*Continued*)**:** Summary of the existing studies describing the attribute of the coastal protection equipped with the Implant Structures. (○) denote the type of investigation, and the parameters studied or investigated in their studies. (-) denotes the type of investigations and parameters not included in their studies.

Infrastructure/Countermeasure	**Type of Experiments**			**Investigated parameters**							**Conclusions/ advantages**
	***in-situ* real large-scale**	**Numerical model**	**Lab-scale model**	**Settlement-resistance and deformations**	**Earthquake- resistance**	**Tsunami-resistance**	**Overtopping flow -scouring resistance**	**Soil-liquefaction resistance**	**Seepage-reduction**	**Overall resistance/stability of the upgraded levee**	
Double-row steel sheet pile walls cofferdam (Zhu et al., 2021)	-	-	○	-	-	○	-	-	○	○	Good dynamic stability, strong deformability, high seepage resistance, and strong engineering adaptability.
Levee reinforcement with double sheet pile walls with partition walls (Hara, 2021)	○	-	-	○	○	○	○	○	○	○	(1) The levee was upgraded with double sheet pile walls to protect against erosion, tsunami, and overflow. (2) The double-sheet pile walls maintain the integrity of the structure. (3) High-quality quality reliable and proven environment-friendly technology.
Applying sheet pile walls to the reinforcement of the river dykes (Geppert et al., 2021)	○	-	-	○	-	○	○	-	-	○	(1) Successful implantation of sheet pile walls to the reinforcement of the river dykes in Germany. (2) Flexible applicability, the reduction of environmental impacts. (3) High quality reliable and proven technology. (4) The method is now an integral part of German standards and technical literature.
Levee upgraded with sheet pile walls driven by the GRB system (Takuma et al., 2021)	○	-	-	-	○	-	-	-	-	○	Successful upgrading of the existing earthen levee against inundation. Noise- and vibration-free operation in a populated and dense urban area.
Levee upgraded with sheet pile wall (Mitobe et al., 2014a)	-	○	○	○	-	○	○	-	○	○	The sheet-pile structure is found to be an effective measure against local scouring to delay the start of the suction of sand under the landward slope through the scour hole.
levees reinforced with sheet pile walls (Koseki et al., 2009)	-	○	○	○	-	○	○	○	○	○	(1) The levee reinforced with sheet pile walls is resistant to L2 tsunami.(2) The stability of sheet pile walls and surrounding ground was confirmed, aided by the liquefaction layer's support.(3) Strategic placement of sheet piles prevented levee breaches during overflow.

References

Fujiwara, K., Taenaka, S., Otsushi, K., Yashima, A., Sawada, K., Ogawa, T., Takeda, K., 2017. Study on levee reinforcement using double sheet-piles with partition walls. JGS Special Publication 5, 11–15. https://doi.org/10.3208/jgssp.v05.003

Fujiwara, K., Taenaka, S., Takahama, K., Yashima, A., 2018. 3-D Behaviour of Coastal Dyke Installed by Double Sheet-piles with Partition Wall.

Geppert, F., 2021. Flood protection through dyke reinforcement at the river "Elbe" in Germany, in: Proceedings of the Second International Conference on Press-in Engineering 2021, Kochi, Japan. CRC Press, London, pp. 484–489. https://doi.org/10.1201/9781003215226-55

Giken LTD., 2024. Highly Resilient Disaster Prevention Levee [WWW Document]. URL https://www.bosai-jp.org/en/solution/detail/1/category (accessed 12.8.23).

Hara, T., 2021. Reinforcement method for reservoir embankment using steel materials, design guide, First edition. Department of Natural Science and Engineering, Faculty of Education and Research, Kochi University (in Japanese)

Hara, T., Okamura, M., Uzuoka, R., Ishihara, Y., Ueno, K., 2012. Damages to River Dikes Due to Tsunami in South-central Coastal Area of Iwate Prefecture in 2011 off the Pacific Coast of Tohoku Earthquake 7, 253–264. https://doi.org/10.3208/jgs.7.253 (in Japanese)

Hirose, T., 2022. Steel Pipe Piles, Tubular Sheet Piles, Steel Sheet Piles Confronting Natural Disasters 7.

Ishihara, Y., Okada, K., Hamada, M., 2018. Comparison of Pile-type and Gravity-type Coastal Levees in Terms of Resilience to Tsunami.

Ishihara, Y., Yasuoka, H., Shintaku, S., 2020. Application of Press-in Method to Coastal Levees in Kochi Coast as Countermeasures against Liquefaction 51.

Jiang, Y., Guo, F., Wang, W., Yang, G., Yue, J., Huang, Y., 2023. Stability Study of a Double-Row Steel Sheet Pile Cofferdam Structure on Soft Ground. Water 15, 2643. https://doi.org/10.3390/w15142643

Koseki, J., Tanaka, H., Otsushi, K., Nagao, N., Kaneko, M., 2009. Model tests on levees reinforced with sheet piles. J-STAGE 61, 1065–1068. https://doi.org/10.11188/seisankenkyu.61.1065

Mimura, N., Yasuhara, K., Kawagoe, S., Yokoki, H., Kazama, S., 2011. Damage from the Great East Japan Earthquake and Tsunami - A quick report. Mitig Adapt Strateg Glob Change 16, 803–818. https://doi.org/10.1007/s11027-011-9297-7

Mitobe, Y., Adityawan, M.B., Roh, M., Tanaka, H., Otsushi, K., Kurosawa, T., 2016. Experimental Study on Embankment Reinforcement by Steel Sheet Pile Structure Against Tsunami Overflow. Coastal Engineering Journal 58, 1640018-1-1640018–18. https://doi.org/10.1142/S0578563416400180

Mitobe Y., Adityawan M.B., Tanaka H., Kawahara T., Kurosawa T., Otsushi K., 2014a. Experiments on scouring behind coastal dikes induced by tsunami overflow. J. JSCE, Ser. B1 70, I_1147-I_1152. https://doi.org/10.2208/jscejhe.70.I_1147

Mitobe Y., Otsushi K., Kurosawa T., Adityawan M.B., Roh M., Tanaka H., 2014b. Effects of Embankment Reinforcement with Steel Sheet Piles against Tsunami Overflow. Journal of Japan Society of Civil Engineers, Ser. B2 (Coastal Engineering) 70, I_976-I_980. https://doi.org/10.2208/kaigan.70.I_976

Noda, T., Takeuchi, H., Nakai, K., Asaoka, A., 2009. Co-Seismic and Post-Seismic Behavior of an Alternately Layered Sand-Clay Ground and Embankment System Accompanied by Soil Disturbance. Soils and Foundations 49, 739–756. https://doi.org/10.3208/sandf.49.739

Otsushi, K., Fujiwara, K., Yoshihara, K., Nishibe, K., Kurosawa, T., Toda, K., Okuda, Y., Kurosaki, K., 2016. Coastal Dyke and Tide Barrier Technologies for Large Earthquakes and Tsunami Runups. Nippon Steel & Sumitomo Metal Technical Report UDC 627 . 235 : 550 . 344 . 4.

Rettura, D.M., Alessandrini, M., Abeywickrama, L., Green, J., Philpott, B., 2018. Island Barn Reservoir – Embankment Leakage remedial works, in: Smart Dams and Reservoirs. Presented at the 20th Biennial Conference of the British Dam Society, ICE Publishing, Swansea University, Swansea, UK, pp. 49–61. https://doi.org/10.1680/sdar.64119.049

Takuma, T., 2019. Upgrading Existing Levees' Seismic Resiliency with Pressed-in Double Sheet Pile Walls. Presented at the Proceedings of the 7th International Symposium on Geotechnical Safety and Risk (ISGSR 2019)., Research Publishing Services, pp. 804–809. https://doi.org/10.3850/978-981-11-2725-0-IS4-13-cd

Takuma, T., Kambe, S., Nagano, M., 2021. Upgrading earthen levee with press-in pile and the GRB system. Proceedings of the Second International Conference on Press-in Engineering Kochi, Japan.

Yokoki, H., Uchida, T., Akamatsu, Y., Seto, S., Onda, S., Yamada, T., Nishimura, S., Tebakari, T., Fujiyama, C., Sakakibara, H., Shigihara, Y., Yokojima, S., 2022. Special Issue On The Storm And Flood Damage 2019 In Japan. Journal of JSCE Vol. 10, 1-7, 2022.

Zhu, Y., Li, X.J., Shi, Z.M., Peng, M., Xuan, L.J., Gao, J.Y., Cai, S., 2021. Dynamic Behavior of Double Steel Sheet Pile Cofferdam under Different Wave Actions. IOP Conf. Ser.: Earth Environ. Sci. 861, 072019. https://doi.org/10.1088/1755-1315/861/7/072019