Article | Received 21 October 2025; Revised 28 October 2025; Accepted 5 November 2025; Published 22 May 2026
https://doi.org/10.55092 pe20260008

Research on overtopping protection and reinforcement of small- and medium-sized river levees: a case study of Japan's overtopping levees

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Abstract: Frequent extreme rainfall events in recent years has escalated the risk of overtopping failure for China's small and medium-sized rivers, where earthen levees remain the predominant flood-protection structures. Compounded by legacy low construction standards and the increasing concentration of population and assets, there is an urgent need to leverage engineering experiences from regions with comparable conditions and to advance research on levee reinforcement. Japan, which shares similar flood-management conditions and water-governance principles with China, has accumulated extensive knowledge and practical experience in this field. Since the 1960s, Japan has developed five major single reinforcement technologies through experimental studies, and subsequently established four engineering-type overtopping-resilient measures in the twenty-first century: the Armor Levee, Super Levee, Frontier Levee, and Crisis Management-type Hard Measures. At present, Japan is implementing approximately 1800 km of Crisis Management-type Hard Measures nationwide while continuing research on Resilient River Levee. This paper reviews the evolution of Japanese overtopping levees, associated surface protection structures, and reinforcement materials, providing insights for improving overtopping protection and resilience of levees along small and medium-sized rivers in China.

Keywords: overtopping levee; overtopping protection; earth levee; Japan

1. Introduction

Under the impetus of global climate change, the intensification and abnormality of extreme rainfall in China have escalated the overtopping risk for levees along small and medium-sized rivers. Rapid urbanization further exacerbates threats to life and property in protected areas. Recent examples include the Tanli Canal overtopping failure during the Haihe Basin's "23·7" flood and the over-70 m breach of the Sixin Levee in Xiangtan during the "7·28" flood in 2024 [1,2]. China is currently upgrading levees nationwide, prioritizing key reaches and simultaneously promoting standardization of deficient levees along small and medium-sized rivers. Within the flood control system for medium and small-sized rivers, earthen levees predominantly constructed in earlier phases still constitute a significant proportion and account for a large percentage of substandard lengths. Therefore, there is

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an urgent need to explore overtopping protection and reinforcement measures to enhance flood resilience. As domestic research in this field is relatively insufficient, Japan—which shares similar flood-management conditions with China—offers a valuable precedent. Since the late twentieth century, Japan has systematically developed, tested, and promoted overtopping-levee technologies under government-led initiatives, accumulating extensive experimental and engineering experience that remains relevant today.

Japanese rivers are characterized by rapid runoff formation, high peak discharge, and steep, short channels [3]. Under China's classification criteria for small- and medium-sized rivers (drainage area between 200 km² and 3000 km²), the vast majority of these rivers fall into this category. Their levees are predominantly earthen and highly susceptible to scouring, with overtopping accounting for approximately 80% of failures. Catastrophic precedents include the 2015 Kinugawa River breach that inundated one-third of cities in Kanto and Tohoku regions, the 2018 Odgawa River breach that submerged one-quarter of Mabi Town, and 142 national failures during the 2019 East Japan Typhoon, 86% due to overtopping, inundating 350 km² of land [4]. This paper reviews the policy evolution, experimental development, and engineering practices of Japan's overtopping protection technologies, with a specific focus on the currently implemented Crisis Management-type Hard Measures. The objective is to provide technical reference for enhancing overtopping protection and resilience of levees along small- and medium-sized rivers in China.

2. Evolution of levee protection types

Japan's overtopping-levee development reflects ongoing trade-offs among technical feasibility, cost, and flood-control policy. This progression is characterized by four primary stages: Armor Levee, Super Levee, High-Standard Levee, and Crisis-Management-Type Hard Measures (Figure 2). Currently, Japan is exploring the Resilient River Levee to address the challenges of climate change. Research methodologies for overtopping protection are primarily categorized into the Surface-Covering Type and the Cross-Section Widening Type: (1) Protective reinforcement measures are implemented on the existing levee body, with the levee surface being partially or fully covered to gain enhanced overspill resistance performance; (2) The width of the levee body on the downstream slope is increased to resist the infiltration and scour caused by overtopping flow [5]. The fundamental objective is to ensure that levees remain stable during overtopping or, at minimum, achieve a significant breach delay, thereby securing critical time for evacuation and minimizing casualties.

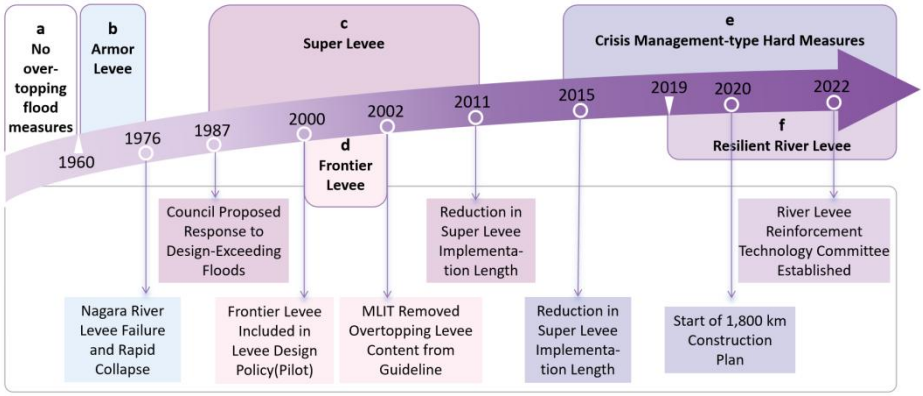


Figure 1. Evolution of overtopping levees.

Since the late 1960s, after the Uetsu heavy-rain disaster, Japan began exploring overtopping-tolerant levees, starting with the Armor Levee as the inaugural surface-cover approach. But after the 1976 heavy rain caused cracks and rapid failure on the Nagara River, researchers questioned full-surface cover because internal defects are hard to detect and maintain, halting further development.

In the 1980s, to enhance flood safety in densely populated metropolitan areas, the River Council proposed Super Levee projects across six rivers in five major basins. Diverging from the Armor Levee, this cross-section-widening design expanded the downstream width to 30 times the levee height (200–300 m) with slopes below 3%, enhancing both anti-scour and anti-seepage capacities while facilitating urban land use (Figure 2). Nevertheless, constrained by exorbitant costs, protracted construction periods, and land-acquisition complexities, the initial target of 873 km was drastically curtailed to 120 km, with limited completion to date [6].

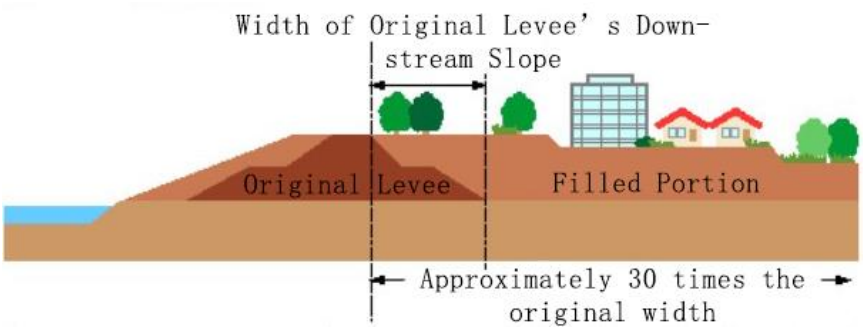


Figure 2. Super levee.

In the 1990s, after Super Levee setbacks, Japan pivoted back toward surface-covering protection and proposed the High-Standard Levee, using full-surface reinforcement to mitigate breach risk. It was formally incorporated into the 2000 Design Guidelines. However, in 2002, the MLIT abruptly rescinded the guidelines. The common view is that such levees—capable of resisting overtopping through reinforcement alone—posed a budgetary rivalry to dam projects for funding and political priority, once again leading to the stagnation of overtopping-levee research.

After 2010, spurred by the pressures of climate change and catastrophic floods in Kanto and Tohoku regions, Japan recognized the necessity and urgency of research on overtopping-levee and shifted to more economically viable and implementable localized surface-covering protection methods. Starting in 2020, Crisis-Management-Type Hard Measures were deployed across 1,800 km of levees nationwide, reinforcing only critical erosion-prone sections to delay the levee failure process as much as possible, thereby maximizing evacuation time.

Since 2020, research has entered a new phase, transitioning from the concept of emergency breach delay to long-term reliability. MLIT established a research committee to develop the Resilient River Levee, aiming for a higher level of protection than Crisis-Management-Type Hard Measures and preparing for the next generation of flood-risk reduction.

3. Experimental development of overtopping-protection technologies

Over a significant period, Japan has conducted extensive investigation and research into overtopping levees under the leadership of government ministries. From the 1970s to the end of the 20th century, the former Ministry of Construction developed five main protection technologies: asphalt pavement on levee crown, cable-tied concrete block protection, interlocking concrete block protection, waterproof membrane protection, and improved-soil protection [7]. They constructed models scaled to the levees of upstream sections of small and medium rivers to simulate the process of flood overtopping in indoor experiments (Figure 2). The performance index was the total cumulative overtopping discharge the levee could sustain before failure.

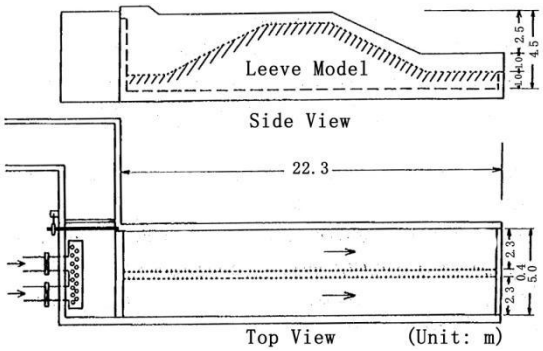


Figure 3. Experimental facility.

Based on statistical analysis of levee overtopping events recorded between 1967 and 1976, researchers discovered that in most instances, the maximum overtopping water depth did not exceed 60 cm, and the duration of overtopping was within 5 hours. Consequently, an ideal overtopping performance goal was proposed: to maintain structural stability under a sustained overtopping depth of 60 cm for a duration of 3 hours, thereby ensuring the necessary evacuation time.

3.1. Asphalt pavement on levee crown

Since the crown of Japanese levees often serves as a road, researchers attempted to modify the levee crown road structure into an asphalt protection system. The road base was constructed using three layers of crushed stone, which were compacted in stages. The road surface was constructed with two layers of asphalt, each 5 cm thick. The uppermost layer used dense-graded asphalt concrete to prevent water infiltration. Experiments found that the primary failure mechanism of the levee crown asphalt protection was: the disintegration and loss of the asphalt surface layer, subsequently triggering water infiltration and collapse of the crushed stone layer, ultimately leading to overall structural failure.

To solve the issue of poor tensile and flexural performance of pavement materials such as asphalt and concrete, a high-strength, heat-resistant polyester mesh was inserted between asphalt layers (Figure 4). Even when cracked, the asphalt stayed bonded under mesh confinement, delaying failure. To reduce gravel permeability, two options were tested: (1) installing an asphalt cut-off wall perpendicular to the water flow direction to block the seepage path; (2) spraying asphalt emulsion into the crushed stone layer. The former resulted in upstream side levee crown uplift and cracking caused by seepage pressure; the exposed component formed a cantilever stress state and was prone to fracture, leading to limited protection effectiveness. The latter, by enhancing water tightness, proved to be more effective in delaying collapse.

The optimal construction scheme for levee crown asphalt protection is: the crushed stone base course is compacted layer-by-layer with asphalt emulsion sprayed in between; the pavement is laid with two gradations of asphalt (coarse and dense), with a synthetic fiber geogrid embedded in the middle and its connection points secured by wire ties.

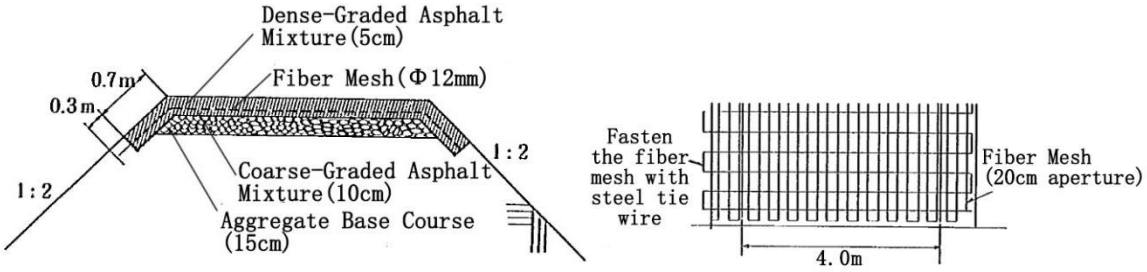


Figure 4. Construction diagram of levee crown protection works.

3.2. Cable-tied concrete block protection

Surface blocks with high roughness are susceptible to inducing strong turbulent shear stress under water flow, and stress concentration can lead to their immediate, one-time dislodgement during the initial flow stage. Researchers therefore developed smoother cable-tied blocks, covering the levee from the upstream shoulder to the downstream section (Figure 5). Experiments showed that when the flow reached the downstream toe, the localized flow velocity increased, causing the blocks to lift. The levee soil was then sucked out through the gaps between the blocks, forming internal cavities. Concurrently, buoyancy forces further uplifted the blocks. Ultimately, the cables connecting the blocks snapped, causing block dislodgement.

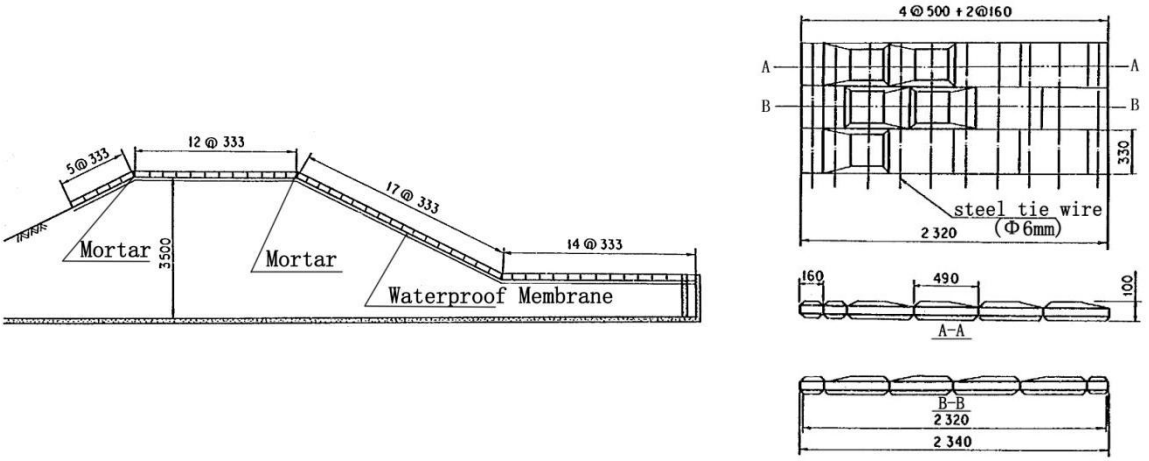


Figure 5. A construction diagram of smooth block protection.

Researchers experimented with two improvements(Figure 6): (1) levee-surface soil mixed with asphalt emulsion at a weight ratio of 1:10, plus an asphalt layer on the upstream slope, with blocks tied by steel wire ropes with a tensile strength of 2.2 t, and anti-detachment knots were set on each block; (2) soil mixed with hydrated lime at the same ratio for soil improvement, blocks connected by tapered ropes with one anti-detachment knot set for every four blocks. In both cases, although some blocks still lifted during the initial flow stage after the modification, the overall flow pattern was

smoother. As scour progressed, 2 to 3 rows from the downstream toe to the rear section of the levee floated up. The erosion rate of the levee soil did not accelerate until localized settlement deformation occurred. This ultimately led to block dislodgement starting from the downstream slope. In comparison, both schemes effectively retarded the failure process and significantly improved the model's scour resistance.

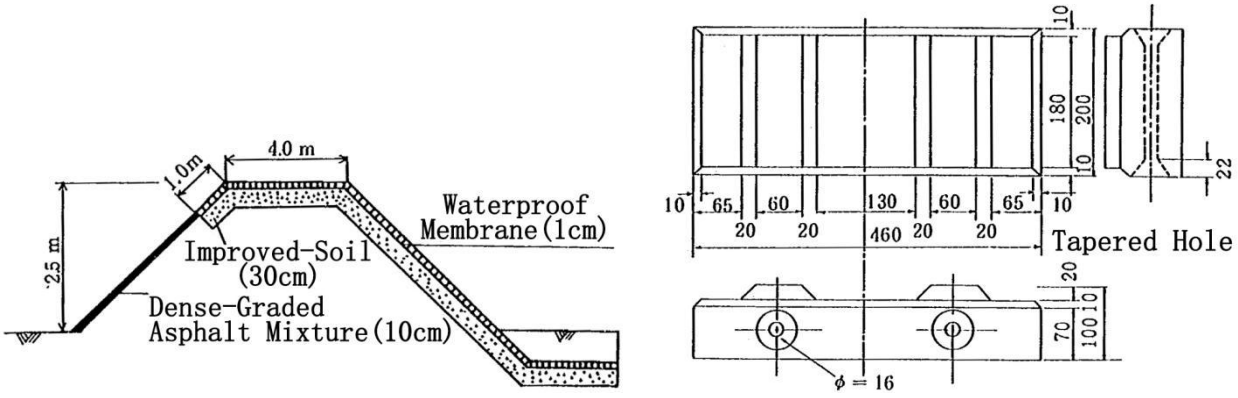


Figure 6. Improvement construction diagram of smooth block protection

In all three types of cable-tied block experiments, the total cumulative overtopping discharge before levee failure exceeded the volume equivalent to a 30 cm overtopping depth sustained for 3 hours (approximately 2600 m^3). This confirmed that the blocks possess a certain capacity to resist overflow.

3.3. Interlocking concrete block protection

Because cable-tied blocks rely on metal connectors prone to corrosion, researchers designed an interlocking blocks with a unit weight of, covering the crown and the downstream section (Figure 7). During the initial stage of the overtopping experiment, the overflow maintained a uniform flow pattern for a long period. However, under the scouring action, the levee soil in the mid-slope to toe section of the downstream slope was sucked out, leading to the tilting and settlement of the blocks, which exposed the interlocking surfaces. In the area where the slope cavity was largest, the localized dislodgement of blocks triggered a chain reaction, causing all remaining blocks to detach within one minute. This demonstrated that the suction of the levee soil is also a key failure mechanism for the interlocking block protection. Although the structure is designed to settle as a whole in conjunction with levee deformation, but its susceptibility to localized failure leading to rapid overall collapse is disadvantageous for post-disaster repair.

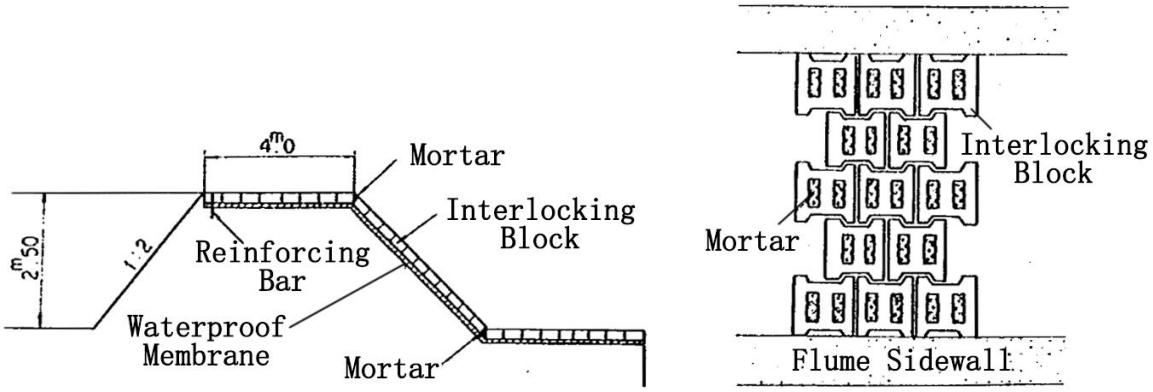


Figure 7. Construction diagram of interlocking block.

3.4. Waterproof membrane protection

Covering erosion-prone areas of levee with impermeable plastic or rubber membranes can improves resistance to overtopping scour. Researchers conducted overtopping experiments by fixing the membrane's sides to the flume walls using adhesive. The results showed that the levee soil beneath the membrane was almost completely protected from erosion, and their low weight and easy installation make them suitable for emergency use. However, the practical engineering applicability of this method is limited. This is primarily because, in the laboratory setup, the membrane relied on adhesive forces to the flume walls to resist the hydraulic tension, which is not representative of field conditions. Additionally, material aging poses a concern for long-term deployment, requiring further research on materials and construction techniques.

3.5. Improved-soil protection

Mixing the upper 1–2 m of levee soil with hydrated lime or asphalt emulsion can reduce the levee's permeability and enhance its strength. In model tests, only the upper 50 cm was replaced with improved soil. During the first three curing weeks, the crown soil samples' uniaxial compressive strength increased, especially with the hydrated lime-treated soil. In overtopping experiments, erosion initiated behind the downstream toe. Tensile stresses from the self-weight of the improved layer exceeded its tensile capacity, leading to tensile cracks appearing in the asphalt emulsion-treated soil at the downstream shoulder and in the hydrated lime-treated soil at the levee crown. These cracks then propagated, resulting in the improved layer fissuring into block fragments. Once the original soil was sucked out, the protective layer collapsed. The method has limited tensile resistance and is prone to fissuring. The rapid failure following the weakening of the original leeve support indicates that this method requires reinforcement measures at the downstream toe to enhance the levee's overall tensile and scour resistance.

3.6. Comparison of individual technologies

Based on the experiments during development phase, the total cumulative overtopping volume per unit length was used as the core metric to compare the retarding capacity of failure, reflects the duration from the onset of overflow to levee failure; a higher numerical value indicates greater slow-failure capacity. Excluding the still-experimental membrane method, the four technologies ranked (best to worst) are: cable-tied blocks, asphalt-paved crown, improved soil, interlocking blocks. Cable-tied blocks performed best, with a total overtopping capacity volume of approximately 8×10^3 m^3/m, which is about twice that of the asphalt crown protection, and the corresponding volume at which erosion occurred on its downstream slope (approximately 6×10^3 m^3/m), nearly six times higher than that of the other methods.

However, considering overtopping resistance, operation and maintenance costs (Table 1), every single technology has its limitations and specific application boundaries. Cable-tied block protection performs best slow-failure performance but is costly; asphalt pavement has the best overall cost-effectiveness; interlocking block protection, improved soil, and membranes serve mainly as supplementary or

emergency options. Addressing complex overtopping risks requires moving beyond a single technology. Future research must shift towards composite protection systems based on multi-technology synergy to enable complementary advantages and targeted protection for different levee sections.

Table 1. Comparison of performance and applicability.

Protection Technique	Applicability	Advantages	Disadvantages
Asphalt Pavement on Levee Crown	Suitable for river sections with low breach risk and good maintenance conditions; can serve as routine protection	Second-highest protection strength; highest cost-effectiveness; easy repair, can be patched locally	Relatively high construction cost; requires regular maintenance and prompt repair if damaged
Cable-tied Concrete Block	Suitable for areas with high breach risk and high potential losses (e.g. levee backs are schools, residential areas)	Highest protection strength; maximum total overtopping flow before breach; significant delay of failure	High construction cost; low cost-effectiveness; block coverage makes inspection of levee hazards difficult
Interlocking Concrete Block	Structural improvement combining interlocking and hinged connection	Can accommodate levee deformation and overall settlement; conforms closely to levee surface	Local detachment may trigger chain failures
Waterproof Membrane	Suitable for emergency reinforcement and short-term use; can serve as auxiliary measure	Lightweight material; rapid construction	Construction technique not fully mature; material durability is poor
Improved Soil	Suitable as an auxiliary measure combined with other protection methods	Low investment cost; potentially high cost-effectiveness	Limited tensile and erosion resistance; performance highly dependent on construction quality and maintenance

4. Integrated stage of overtopping-protection measures

Since the 2000s, Japan's research on overtopping levees has entered a system integration phase, shifting from single-technology development to optimal combination and integrated engineering measures. After the former Ministry of Construction merged into the MLIT in 2001, a coordinated government–industry–academia system was established, advancing studies on Crisis Management-type Hard Measures and the Resilient River Levee [8,9]. The former category focuses on levee crown asphalt protection and downstream toe block structures and has already been applied in practice; the latter remains under study, with surface-covering type structures progressing more rapidly. Final design choices are ultimately formulated by comprehensively weighing the experimental conclusions against actual engineering feasibility.

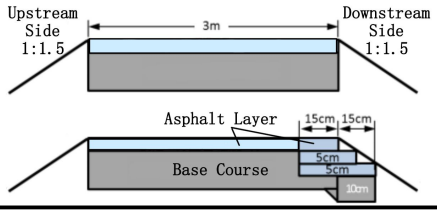
4.1. Crisis management-type hard measures

Crisis Management-type Hard Measures lies in combining localized structural reinforcement with energy dissipation to maintain the structural integrity of critical sections of earthen levees, protect

erosion-prone areas, and thereby delay overtopping-induced failure. Levee crown protection functions by forming a temporary load-bearing surface layer after soil erosion, preserving crown elevation, while downstream toe protection mitigates scour by reducing near-bed flow velocity and altering flow regimes to dissipate kinetic energy.

Experiments concentrated on protection of two critical zones: the levee crown and downstream toe. Levee crown experiments (Table 2) show that asphalt layers form a temporary cantilever structure once the underlying soil is eroded, thereby sustaining crown elevation and delaying failure. Placing multi-layer asphalt along the downstream shoulder widens the protected zone and enhances delay performance, a technique particularly suited for mild-slope levees. Under identical temperature conditions, recycled dense-graded asphalt exhibits higher flexural strength than Modified Asphalt Type I, enabling longer cantilever spans.

Table 2. Asphalt structure experiment.

No.	Asphalt Type	Subgrade Material	Structure
1	Recycled Dense-Graded Asphalt	RC-40	
2	Modified Asphalt Type I		
3	Recycled Dense-Graded Asphalt		

The downstream toe reinforcement experiments explored the energy dissipation mechanism of slope roughness features by systematically altering the presence of the base layer as well as the shape, height, and arrangement of the roughness features (Figure 2). Increased slope roughness reduces the near-bed velocity, and protrusions induce localized hydraulic jumps that mitigate scouring. Sparse arrangements tend to accelerate the overflow through the gaps between protrusions, leading to side-flow hydraulic jumps. Conversely, dense arrangements submerge the features, and if the protrusion height is further increased, the flow is prone to separation or bypassing, making hydraulic jumps less likely to occur. The most significant scour reduction effects were observed with densely arranged 8 cm high diamond protrusions, 5 cm high bar protrusions, and sparsely alternating arrangements of 5 cm and 10 cm rectangular protrusions.

In addition, to address the erosion-prone interface between the upstream edge of the concrete toe block and the levee slope, a downstream-inclined end wall was investigated. This inclined structure was found to dissipate flow more effectively than a vertical structure by dispersing the incoming water, thereby preventing localized scour at the junction.



Figure 8. Block construction diagram.

4.2. Resilient river levee

The protective mechanism of the surface-covering type in Resilient River Levee primarily lies in the synergistic improvement of the overall stability of the earth levee through a multilayered defense system. By constructing a high-strength flexible revetment with cable-tied concrete blocks, the structure effectively resists the shear stress induced by flow scouring. Simultaneously, anti-absorption sheets are employed for aeration and filtration, which dissipates the uplift pressure within the levee body to prevent structural damage to the revetment while effectively inhibiting the loss of soil particles. The downstream surface-covering type structure can be generalized as "anti-absorption material + concrete blocks + cover soil". Although current prototypes have not yet fully reached the target overtopping-performance criteria, experimental results robustly confirm their capacity to resist significant overtopping flows. In flume experiments, the downstream slope was covered with cable-tied concrete blocks interconnected by zinc–aluminum alloy–coated wires. These experiments were conducted using models built from two distinct levee materials at 1:2 and 1:3 slope configurations. After subjecting both models to a simulated overflow condition of a 30 cm depth sustained for 3 hours, both models showed no significant deformation, and surface materials remained intact (Figure 9).

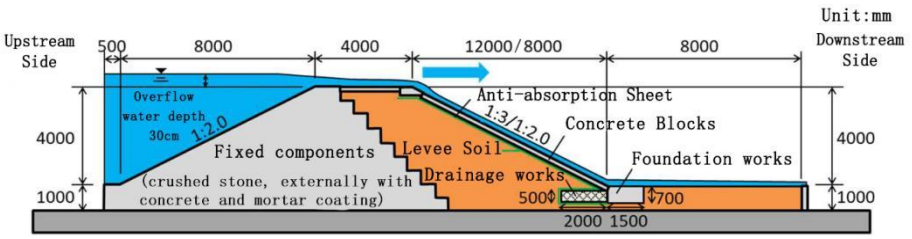


Figure 9. Experimental results.

5. Engineering practice

Currently, Japan's overtopping-levee reinforcement measures already piloted or under development mainly include: Armor levee, Frontier levee, Crisis Management-type Hard Measures, and Resilient River Levee. Examining the practical implementation process, the majority of protection structures employed thus far have been surface-covering types, while recent efforts have progressively focused on modifying the levee body structure itself. The evolution of these countermeasures shows a shift from complex to simple and from full-section to localized protection. Furthermore, the design goal, initially shifting from long-term defense to short-term emergency response, has reverted to long-term protection in the latest research, resulting in the first-ever establishment of design standards for overtopping performance. Due to technical and policy limits, 20th-century projects were short in length. Since the 21st century, Crisis Management-type Hard Measures have become the most feasible, widely applied, and longest-implemented measures in terms of construction length.

5.1. Armor levee

The Armor levee is an engineering countermeasure that applies full-surface protection to the levee (Figure 10). It is primarily used to cope with design-exceeding floods or as a temporary reinforcement during river sediment management works. The Public Works Research Institute proposed its basic cross-section, which includes: an upstream anti-scour revetment, an asphalt-paved crown with protection and traffic function, and a downstream side with waterproof sheets, concrete grids, vegetation, and drainage piles to provide anti-scour, drainage, and seepage-control functions. This structure is characterized by its ease of construction and low cost, allowing the protection zones to be flexibly selected based on river management progress and economic conditions. From 1988 to 1999, only 13 km were piloted across five rivers; subsequently, due to policy adjustments, it did not develop into a large-scale standardized measure, and most examples remain merely as case studies.

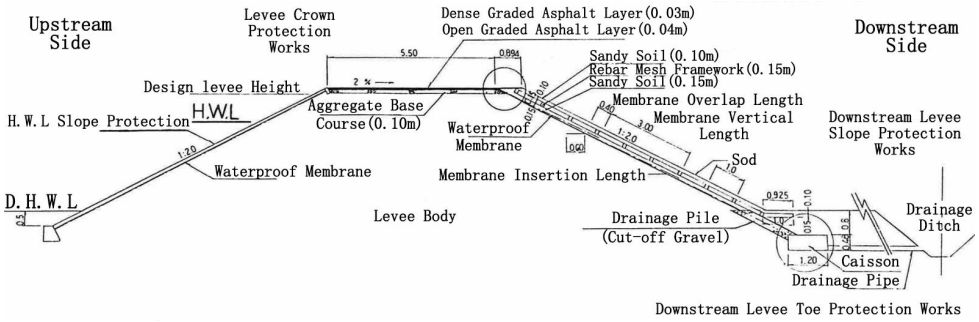


Figure 10. Armor levee diagram (Unit: m) [10].

5.2. Frontier levee

The frontier levee is a durable measure intended for long-term resistance to extreme floods [10]. Its design incorporates an asphalt crown, specially protected shoulders, and a downstream section designed for drainage, aeration, seepage control, and scour resistance (Figure 11). Proposed in 1996, it was included in Japan's five-year flood-control plan, with a planned 250 km length. However, in 2001 the government discontinued the development program and deleted overtopping-levee content from new design guidelines. Only 13 km were built on four rivers (1990–2003). High maintenance and cost (e.g., 48 billion yen for 1.1 km on the Kumode River) hindered adoption.

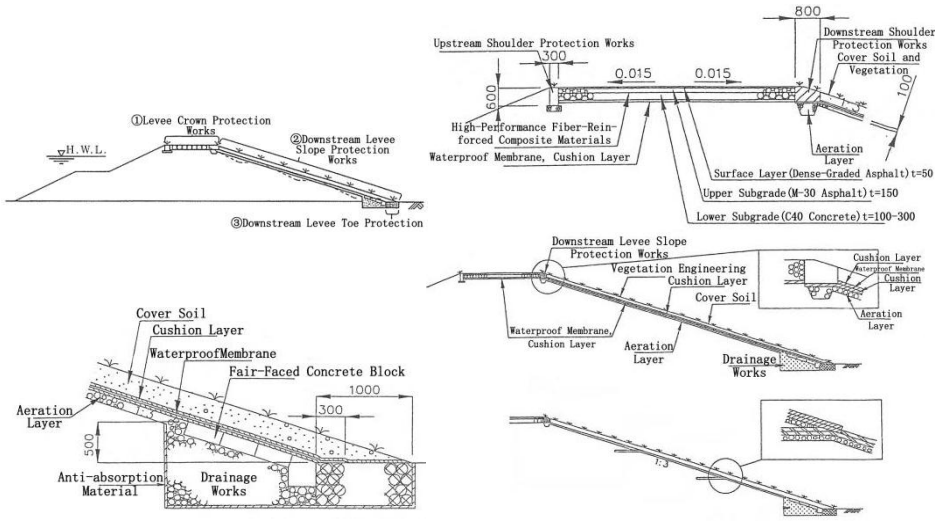


Figure 21. Frontier levee diagram (unit: mm).

5.3. Crisis management-type hard measures

The measures are structural emergency reinforcement measures that only protect critical zones (Figure 12). They are designed to cope with design-exceeding floods in the short term and represent the most widely implemented reinforcement measure currently in use [11]. The system utilizes an asphalt cantilever maintains crown height, precast concrete blocks locally reinforce the shoulder, and cable-tied blocks at the downstream toe resist scour (Figures 13, 14), slowing breach progression and gaining evacuation time. After the 2015 Kinugawa disaster, Japan planned about 1,800 km for national application: roughly 1310 km of crown protection and 630 km of downstream-toe protection. Construction began in 2020. Using various precast blocks, it offers fast construction and low cost, making it suitable for high-risk areas under budget constraints. Their effectiveness has been validated in actual flood events, such as the overtopping incident on the left bank of the Toki River: a reinforced levee section remained stable after enduring an overflow of 10 cm sustained for 8 hours. Significantly, erosion was observed only on the downstream slope section where vegetation alone provided protection.

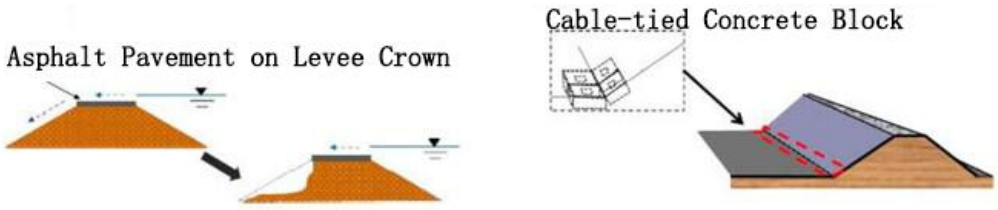


Figure 32. Crisis management-type hard measures.

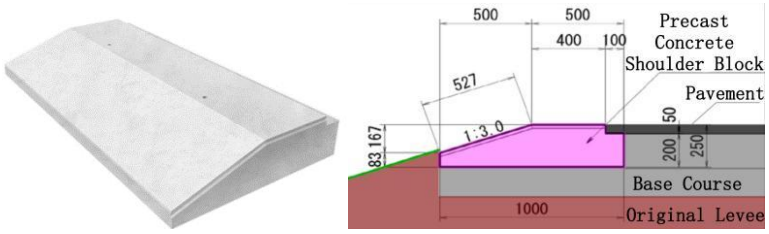


Figure 43. Precast concrete shoulder block.

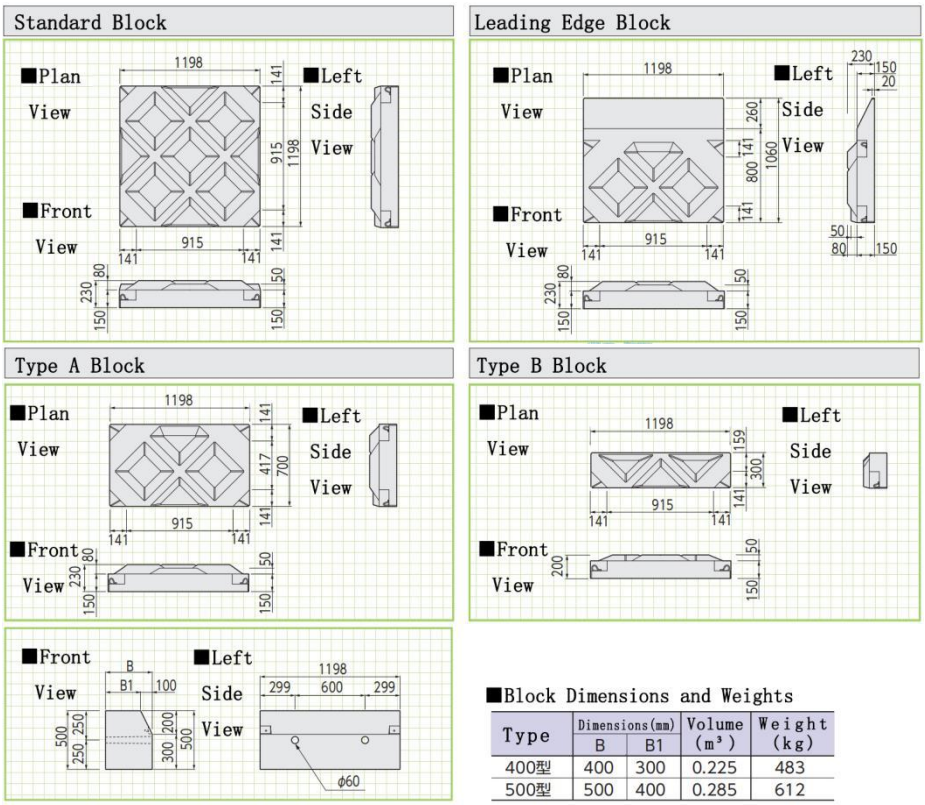
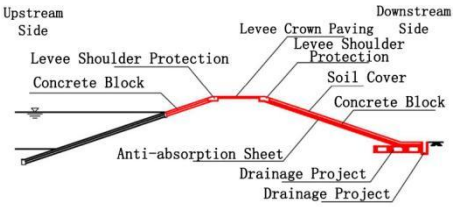


Figure 54. Concrete block at the toe of the lower slope side levee.

5.4. Resilient river levee

The Resilient River Levee is a reinforcement measure designed with explicit overtopping performance targets for long-duration flood resistance (Figure 15) [12]. Based on statistical data from major overtopping incidents since 2015, the overtopping water depth in most cases fell between 20 cm and 50 cm, with over half being below 30 cm. Considering the required 3-hour duration for resident evacuation, the following overtopping performance target was established: to remain stable under flood conditions with an overtopping depth of 30 cm sustained for 3 hours. Development officially began after the 2019 East Japan Typhoon [13]. Designs include three types: surface-covering type structure (including widened sections), independent-support type structure (including special stand-alone levees), and other hybrid structures that rely on surrounding fill for stability. This measure is currently still in the research and validation phase. As research progresses, pilot projects have commenced in specific river sections since 2021, and it is widely regarded as the future direction for levee reinforcement in Japan.



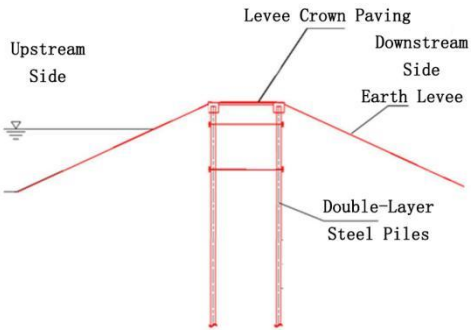


Figure 65. Examples of resilient river levee structures.

6. Implications

China and Japan share similar flood management challenges, including numerous small- and medium-sized rivers, predominantly earthen levees, and densely concentrated populations and assets, all facing risk of overtopping during extreme weather. Levees constitute a critical component of China's flood control system, with a total length of 325,000 km by the end of 2023 and protecting 640 million people. Given the constraints during early construction, extensive existing levee networks are prone to hidden hazards, and difficult to rebuild comprehensively; thus, reinforcement is essential for short-term capacity improvement.

Both countries have transitioned from reliance on high-standard levees to system-based management and resilience enhancement. China shifted the policy from flood control to flood management in the early 21st century, with the 14th Five-Year Plan emphasizing levee reinforcement on small- and medium-sized rivers. Similarly, Japan's approach evolved from risk control to risk management, adopting non-quantitative flood protection and introducing overtopping countermeasures as a transitional phase in the early 21st century.

In China, levee failures are primarily caused by overtopping and seepage erosion. Japanese levee overtopping protection technologies, with proven research and practice, offer valuable references for enhancing China's levee resilience:

(1) Directly applicable measures: Some Japanese partial protection measures can be piloted in China. For example, asphalt paving on the levee crown with shoulder protection is mature, cost-effective, and compatible with China's flood-control roads. Downstream slope block placement provides counter-pressure and seepage guidance; its modular design allows rapid deployment for emergency reinforcement. Further research could improve block permeability and performance.

(2) Measures requiring adaptation: Some techniques, such as upstream slope waterproof membranes, require study under China's soil and seepage conditions, despite established Japanese practices.

(3) Gradual reinforcement strategy: Japan's temporary protection-long-term reinforcement-gradual enhancement approach exemplifies resilience-oriented management. Lessons derived from balancing governance, investment, and policy priorities can inform China's future levee resilience planning.

Acknowledgments

The work was supported in part by the Five Talents Program of China Institute of Water Resources and Hydropower Research (WH0145B062022).

Authors' contribution

Conceptualization, Shiting Xiao and Bingshun He; methodology, Shiting Xiao; validation, Shiting Xiao, Bingshun He and Qiuling Yao; formal analysis, Shiting Xiao; investigation, Shiting Xiao; resources, Bingshun He; data curation, Shiting Xiao; writing—original draft preparation, Shiting Xiao; writing—review and editing, Bingshun He and Qiuling Yao; visualization, Shiting Xiao; supervision, Bingshun He; project administration, Bingshun He; funding acquisition, Bingshun He. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

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