

**Numerical Model Coupling Flood Hydrodynamics and
Architectural Spatial Features for Cultural Heritage
Sites in Kyoto City**

CHEN XI

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**Numerical Model Coupling Flood Hydrodynamics and
Architectural Spatial Features for Cultural Heritage Sites
in Kyoto City**

A dissertation submitted in partial fulfillment for the requirement of
Doctoral Degree in Civil and Earth Resources Engineering

by

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Abstract

Under the new environmental context of frequent extreme weather events and high-density urban development, flood disasters have become one of the major risks facing historic cities and cultural heritage sites. Heritage disaster mitigation management requires quantitative assessment of key flood intensity indicators such as peak water depth, flow velocity, and inundation duration to identify spatial risk distributions. However, there is a severe shortage of locally detailed disaster process data to support decision-making. Furthermore, in small-scale urban areas like heritage sites, flood processes are often significantly influenced by architectural spatial features (such as overhanging eaves, piloti, and porous fences). Nevertheless, modeling tools capable of accurately representing these spatial features within a two-dimensional hydrodynamic framework are also lacking. Consequently, the demand for refined data in heritage disaster prevention conflicts with the spatial representation capabilities of existing hydrodynamic models for small-scale sites, creating an urgent interdisciplinary research gap that requires attention.

To address these challenges, this paper integrates cultural heritage disaster mitigation requirements with hydrodynamic modeling methods. Focusing on the core scientific issue of how architectural spatial characteristics influence flood processes through hydrodynamic mechanisms, the research establishes a coupled numerical modeling and evaluation methodology that links flood hydrodynamics with architectural spatial features. The research encompasses six dimensions: spatial feature extraction, hydrodynamic impact analysis, numerical model construction, mitigation mechanism interpretation, mitigation effect quantification, and resilient optimization design. The objectives are: first, to translate the influence of typical architectural spatial characteristics on flood spreading processes into parameter expressions that can be incorporated into 2D hydrodynamic models; second, to conduct comparative simulations and mechanism analyses of traditional passive flood adaptation measures at the heritage site scale to generate comprehensive effectiveness evaluations and optimization design bases for conservation decision-making. This research addresses practical heritage disaster prevention challenges by developing reusable modeling tools, evaluation methods, and research

workflows. Additionally, it explores the fundamental connections between heritage architecture and flood modeling, integrating spatial characteristics into numerical models for validation and comparison. This approach provides a clear and feasible pathway for interdisciplinary research between the two academic fields.

In the specific research, this paper first developed a slot-extended 2D hydrodynamic model targeting the hydrodynamic process where floodwater transitions from unpressurized to pressurized flow as it passes through the space beneath piloti structures. This model extends the traditional 1D slot concept to a computational framework suitable for 2D unstructured meshes, enabling SWEs to reproduce the flood under piloti. Next, the extended model was validated under steady and unsteady states flume experiments. By comparing peak water depths, process curves, and critical moment characteristics, the model's ability to reproduce flood propagation processes was verified. Finally, comparative simulations of real-world scenarios demonstrate that piloti significantly alter flood spatial distribution within. Neglecting this spatial feature leads to biased risk assessments in critical zones. Additionally, piloti exhibit distinct impacts on building areas versus surrounding spaces, indicating that their disaster mitigation benefits and external effects require comprehensive evaluation.

To address porous fence or hedge structures in heritage sites, this study conducts systematic hydraulics experiments. Within a controlled setup adjusting porosity, wall thickness, and inflow conditions, the experiments quantitatively analyze how porous walls influence water level differences and momentum loss. Under the assumption of momentum conservation, a drag coefficient calculation method is established, further refined through empirical equation fitting for numerical modeling. Subsequently, models incorporating additional drag terms were validated using experimental data, demonstrating their efficacy in reproducing the hydraulic effects of fences. Case studies further reveal that porous fences of varying configurations and layouts alter spatial connectivity and discharge pathways, thereby reorganizing flood spatiotemporal behavior. These effects are significant in micro-scale simulations and cannot be disregarded.

Finally, this paper conducts scenario simulations using representative Kyoto heritage

sites such as Katsura Imperial Villa and Shimogamo Shrine. A Comprehensive Effectiveness Index (CEI) framework is proposed to quantitatively evaluate the flood mitigation effectiveness of piloti and porous fence in real heritage environments. Based on hydrodynamic indicators, this framework assesses both the protection benefits at the architectural scale and fluctuations in surrounding spatial risks. The study indicates through spatial distribution and indicator variations that, in the Katsura Imperial Villa, piloti show significant structural protection benefits but minor negative landscape impacts. In contrast, porous walls under the current layout produce the negative effect of slightly raising water levels within the heritage site. Further comparative analysis reveals that porous fences hold potential for optimized flood mitigation design in heritage sites, although their effectiveness is highly dependent on inflow direction, discharge pathways, and spatial layout conditions. Consequently, flood protection design for heritage areas should not simply pursue rigid barriers. Instead, it should reasonably balance the disaster mitigation benefits for protected structures with risk transfer and associated costs to surrounding environments, guided by an understanding of hydrodynamic processes.

In summary, this paper establishes a two-dimensional hydrodynamic model suitable for cultural heritage sites by incorporating architectural spatial feature representation, physical experiment support, and comprehensive effectiveness assessment. This approach extends the applicability of flood inundation models to the scale of cultural heritage. The research outcomes not only provide heritage sites with more precise flood intensity metrics and risk distribution identification methods, but also offer quantitative tools for understanding the hydrodynamic mechanisms of traditional passive flood adaptation measures. Consequently, it delivers technical support for spatial interventions and resilience optimization that balances heritage preservation with flood risk management.

Keywords

Cultural heritage, Hydrodynamic modeling, Architectural features, Piloti, Porous fence, Comprehensive Effectiveness Index (CEI)

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“I truly want to thank myself.”

Chen Xi

Written on Christmas Eve, 2025

At UOL, Kyoto, Japan

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1. Introduction

1.1. Background and significance

1.1.1. Climate change and flood risks

Climate change is imposing cumulative impacts on the world's cultural heritage through rising sea levels, increasing temperatures, and more frequent and intense extreme weather events. The International Council on Monuments and Sites (ICOMOS) stated that climate change has become one of the most significant and rapidly growing threats facing global cultural heritage (ICOMOS, 2017). Multiple flood incidents recently have further highlighted this risk: Jordan's World Heritage site Petra suffered severe flooding (2025); Libya's Cyrene archaeological site sustained damage (2023), Germany's Arl Valley Cultural Landscape was impacted by mountain tributaries (2021), and Japan's national treasure historical structures, including Aso Shrine in the Kuma River basin of Kyushu, were damaged by river breaches in 2020. Research indicates that approximately 6% of existing UNESCO heritage sites (around 40 locations) face the risk of submersion within the next two millennia (Marzeion and Levermann, 2014).

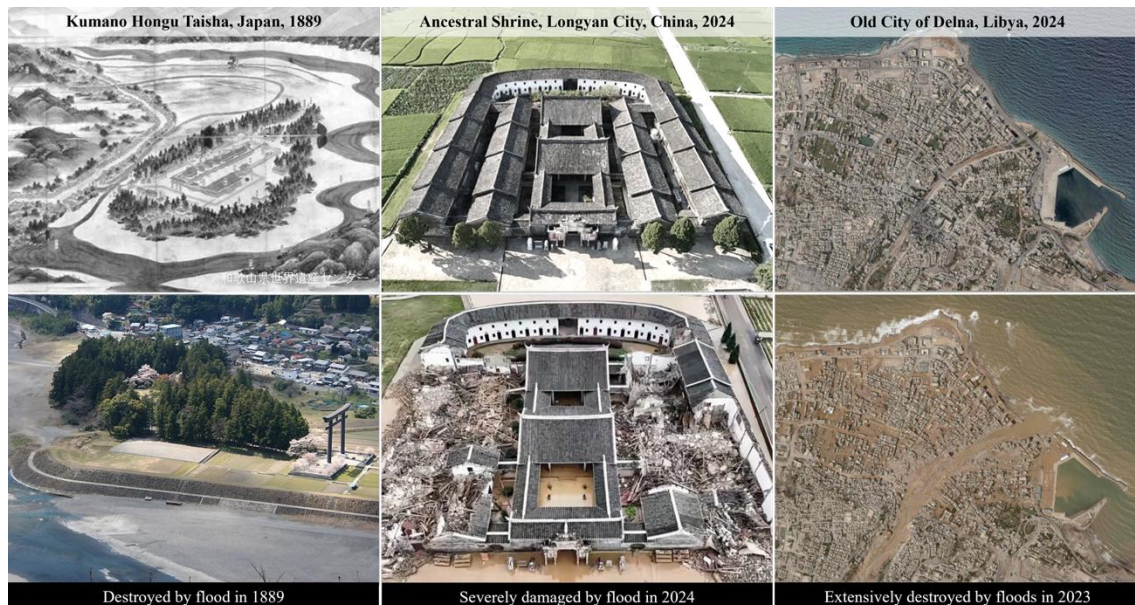


Figure 1.1 Cultural heritages destroyed by floods (before and after disasters)

(<https://www.sekaiisan-wakayama.jp/>, <https://baijiahao.baidu.com>, <https://jiji.com>)

Driven by the combined effects of global climate change and rapid urbanization,

flood frequency and impact are increasing (IPCC, 2023; Li et al., 2025; Mondal et al., 2025) , posing more severe sustainability challenges for the conservation and risk management of historic districts and cultural heritage sites(Arrighi, 2021; Ortiz et al., 2016; UNISDR, 2018) (Fig. 1.1).

1.1.2. Dual disciplinary needs

The real-world issue of cultural heritage flood disasters intersects two academic disciplines, hydrodynamics and heritage conservation, which currently lack effective integration. On one hand, urban flood research primarily focuses on flood simulation, flood mitigation engineering, and the formulation of corresponding planning and policies. Numerical modeling, one of the most critical research methods, has long been well-developed but is primarily applied to large-scale issues like cities or river basins. The ability to use it as a research method to address practical problems at the human-scale level within cities remains limited. On the other hand, heritage conservation mainly involves protective measures, restoration techniques, or risk assessments, often lacking precise flood forecasting. If we consider heritage conservation as the applied objective and flood modeling as the technical approach, it becomes evident that despite their apparent disconnect, they can form a logically coherent pathway with significant research value. This integration expands the application scope of flood models and enables the quantification of flood behavior at heritage sites. Such integration not only addresses the urgent need for research on heritage flood disasters but also represents a natural development trend across disciplines. This practical need has spurred the emergence of a new interdisciplinary field: disaster mitigation of cultural heritage. Grounded in the principles of authenticity and integrity (Blavier et al., 2023), this field centers on research into the sustainable preservation of cultural heritage(Drdácký, 2011; Okubo, 2016) (Fig. 1.2). This dissertation is situated within this new field, addressing the existing gap and demand in this area of study.



Figure 1.2 Disaster mitigation of cultural heritage

1.1.3. Heritage value and urgent challenges in Kyoto

Cultural heritage possesses unique value in multiple dimensions. It not only represents the cultural, social, and spiritual identity of a nation or region, embodying unique historical, artistic, and societal values, but its significance has expanded to the level of resilient societies. The heritage enhances social resilience by strengthening community identity, drives urban development through heritage revitalization and adaptive reuse, and provides solutions to climate challenges by preserving adaptive traditional technologies, thereby making positive contributions to global sustainable development (Guzman, 2025; ICOMOS, 2019; Petti et al., 2020; Thomas et al., 2019). However, as flood risks persistently escalate due to climate change, these functions and values now face direct threats.

As a historic city with a high concentration of cultural heritage sites that has long faced threats from river flooding, Kyoto offers research setting that is both representative and urgent. The city hosts numerous World Heritage sites, Imperial properties, and nationally designated cultural properties, encompassing diverse heritage types such as traditional wooden building complexes, landscape gardens, and historic districts (Fig. 1.3a). These sites not only embody Japanese culture and aesthetics but also serve as vital local tourism resources. Meanwhile, as a basin surrounded by mountains on three sides, Kyoto suffers from persistent river flooding, inevitably affecting its riverside cultural heritage (Fig. 1.3b). However, the government and related institutions have primarily

focused their research on fire and landslide prevention for cultural heritage, with little attention given to flood issues.

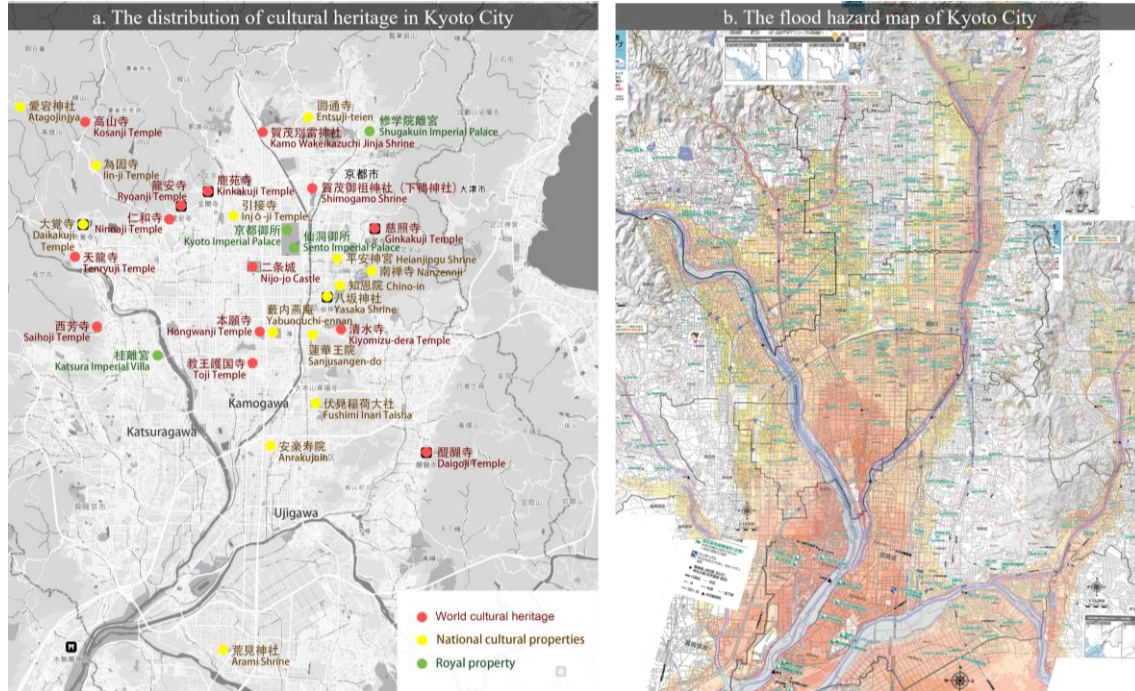


Figure 1.3 (a) The distribution of cultural heritage; (b) The flood hazard map
(source: <https://www.kkr.mlit.go.jp/yodogawa/index.html>)

In the context of climate change driving the continuous accumulation of flood risks, deeply understanding the flood behavior of cultural heritage sites from both process mechanisms and quantitative prediction perspectives, and providing scientific evidence for disaster mitigation and adaptation, has become a critical research topic aligned with global and societal trends, disciplinary demands, and practical needs.

1.2. Overview and justification

Existing research on flood modeling and heritage preservation primarily focuses on several interconnected aspects: (i) the impact of floods on traditional wooden structures derives mainly from hydrodynamic forces, buoyancy, and prolonged inundation, evaluated through indicators such as flood depth, flow velocity, and submersion duration, which directly correspond to flood model outputs; (ii) existing flood studies at cultural heritage sites predominantly focus on large-scale risk assessments, lacking detailed

simulations of individual structures; (iii) flood modeling often oversimplifies buildings, neglecting the hydrodynamic characteristics of local components; (iv) traditional passive flood protection measures are largely based on qualitative understanding, while their specific efficacy and hydrodynamic mechanisms remain unclear; (v) current approaches to enhancing flood resilience in heritage sites mainly rely on soft governance tools like planning controls and emergency plans, with limited focus on adding specific flood countermeasures that meet heritage conservation requirements. For localized urban areas represented by heritage sites, common small-scale structures, such as fences, elevated buildings, and high-platform foundations, significantly alter local water depth, flow velocity, and runoff pathways. These features often constitute passive flood control measures inherent in traditional architectural design and have long defined the spatial features of representative heritage sites. Conventional macro-scale flood modeling rarely identifies such localized effects, leading to underestimation of disaster severity in critical areas. The core distinction between simulating heritage sites and ordinary urban areas is that heritage sites possess representative features directly influencing water distribution within the site, which cannot be ignored at the local simulation scale.

Given these practical challenges and research developments, a clear research gap emerges: on one hand, precise flood prediction data for cultural heritage sites is absent; on the other hand, existing numerical simulation tools fail to meet the unique scale and precision requirements for heritage flood modeling. Consequently, heritage management relies on historical data or rough estimates, limiting scientific understanding and quantitative spatial interventions.

1.3. Research questions

Based on the discussion above, there are five main research questions which will be explored in this dissertation:

- 1) What are the differences in flood dynamics and modeling requirements between cultural heritage sites and urban built environments?
- 2) How do the unique spatial features of cultural heritage sites alter local hydrodynamic

responses under flood conditions?

- 3) How can the identified spatial features be parameterized in a meaningful way and incorporated into numerical models?
- 4) How can we quantitatively understand the disaster mitigation effects of traditional passive flood-adaptive measures at cultural heritage sites?
- 5) Based on the above, how can we propose feasible spatial interventions to enhance the flood resilience of heritage sites?

1.4. Aim and objectives

Based on the background analysis and research questions, the overall objective of this study is defined as follows: within the context of typical cultural heritage sites in Kyoto City, expand and develop a two-dimensional inundation simulation method suitable for small-scale, complex urban environments such as heritage areas. This method will reveal the mechanisms by which microstructures influence flood spreading and spatial risk distribution, thereby providing quantitative analytical tools and layout optimization recommendations for enhancing the flood resilience of cultural heritage sites. Correspondingly, these research questions are addressed through five specific objectives, where each objective is designed to respond to one key question before:

- 1) To distinguish modeling approaches for cultural heritage sites versus general built environments, identifying and categorizing key spatial and structural features directly influencing inundation dynamics within heritage areas.
- 2) To quantify and clarify hydrodynamic response mechanisms induced by representative features (e.g., piloti structures and diverse fence types) through physical modeling and numerical simulation.
- 3) To parametrically represent key heritage spatial features and incorporate them into 2D shallow water equations (SWEs) to develop a small-scale flood numerical model tailored for cultural heritage contexts.
- 4) To establish an evaluation framework for flood mitigation effects of traditional passive flood-adaptive measures, quantitatively assessing their risk reduction and

redistribution roles within and around sites.

- 5) Using the representative cultural heritage sites in Kyoto City as case studies, to propose feasible spatial intervention strategies based on simulation results to enhance flood resilience of heritage sites, and to provide decision support for relevant planning and management.

This study focuses on flood hazards within cultural heritage sites, integrating research methodologies from heritage conservation science, hydrology and water resources engineering, and architecture to explore the potential for interdisciplinary research. It aims to provide reusable models and indicators while offering methodologies and decision support for heritage conservation decisions and future resilience design. (Aste et al., 2019; Smith et al., 2023)。

1.5. Contributions of the study

By linking cultural heritage disaster prevention needs with hydrodynamic theory, this study attempts to establish an interdisciplinary interface between heritage conservation and flood modeling, addressing the challenge of precise flood modeling for cultural heritage sites. Theoretically, it reveals the unique spatial features of cultural heritage that necessitate specialized flood modeling, providing a foundational theoretical and cognitive framework for discussing flood-related issues in heritage contexts. Methodologically, integrating physical experiments with numerical simulations, the study introduces a parameterized expression method within a 2D hydrodynamic model to accommodate diverse heritage features (e.g., overhanging eaves, piloti, and various fences), thereby expanding the applicability of flood modeling to the unique setting of cultural heritage sites. In terms of conclusions and contributions, this study quantifies the hydrodynamic mechanisms of traditional passive flood control measures, revealing their risk redistribution and disaster mitigation principles. For practical application, the paper proposes a reusable research workflow to compare the flood mitigation effectiveness of different measures and layouts, providing quantitative decision support for heritage management agencies in flood adaptation and renovation strategies. Overall, this research

deeply integrates cultural heritage protection objectives with hydrodynamic methodologies. It not only enriches the theoretical and methodological framework for flood risk studies in cultural heritage but also provides a technical pathway and empirical experience for other cultural heritage projects to enhance flood resilience while preserving heritage value.

1.6. Structure of dissertation

This thesis addresses the previously stated research objectives through six key aspects: spatial feature extraction, hydrodynamic impact analysis, numerical model development, mitigation mechanism analysis, quantification of mitigation effects, and resilient optimization design. It is structured into seven chapters:

Chapter 1: Introduction. This chapter outlines the research background and significance, identifies interdisciplinary needs and practical challenges, presents the research questions, objectives, and innovative contributions, and provides an overview of the thesis structure.

Chapter 2: Literature Review. This chapter clarifies relevant concepts, systematically reviews studies on cultural heritage flood risk, flood impacts on traditional wooden structures, modeling approaches for structures in flood simulations, evaluations of flood mitigation measures, and pathways to enhance flood resilience at heritage sites. It identifies limitations in existing research to establish a theoretical foundation for methodological design.

Chapter 3: Methodology. This chapter introduces the study area represented by Katsura Imperial Villa and Shimogamo Shrine. Constructs an overall methodological framework coupling spatial characteristics with hydrodynamics. Presents the design approach for numerical modeling and physical model experiments. Explains data sources, preprocessing procedures, and the fundamental composition of the Comprehensive Effectiveness Index (CEI).

Chapter 4: Modeling Extension and Validation of Piloti. This chapter proposes a parametric method for piloti structures in 2D inundation model, analyzes local flow

characteristics within the elevated layer, validates the expanded model under steady-state and unsteady-state conditions through flume experiments, and assesses the flood prevention applicability and effectiveness of piloti measures in Katsura Imperial Villa.

Chapter 5: Hydraulic Experiments and Modeling of Porous Fence. This chapter introduces typical application scenarios of porous fences in heritage sites. Systematic flume experiments and dimensional analysis are conducted to establish an empirical formula for the drag coefficient of porous fences. This coefficient is then integrated into a 2D inundation model for applicability testing and scenario simulation under steady and unsteady conditions.

Chapter 6: Traditional Countermeasures Evaluation and Optimization Design. Building upon the previous models and parameters, a CEI evaluation framework is established to quantitatively assess the flood mitigation effects and risk redistribution of traditional flood mitigation measures such as piloti and porous walls. The study combined with case studies of typical cultural heritage sites in Kyoto to explore resilience enhancement strategies and spatial layout optimization approaches for future scenarios.

Chapter 7: Conclusion. This chapter summarizes the main research conclusions and academic contributions of this paper, discusses the engineering and management implications of the findings, identifies existing limitations in the research, and outlines future research directions for more complex heritage scenarios and multi-hazard contexts. A systematic methodology for analyzing flood risks and enhancing resilience in cultural heritage sites is progressively established. The specific framework is illustrated in Figure 1.4:

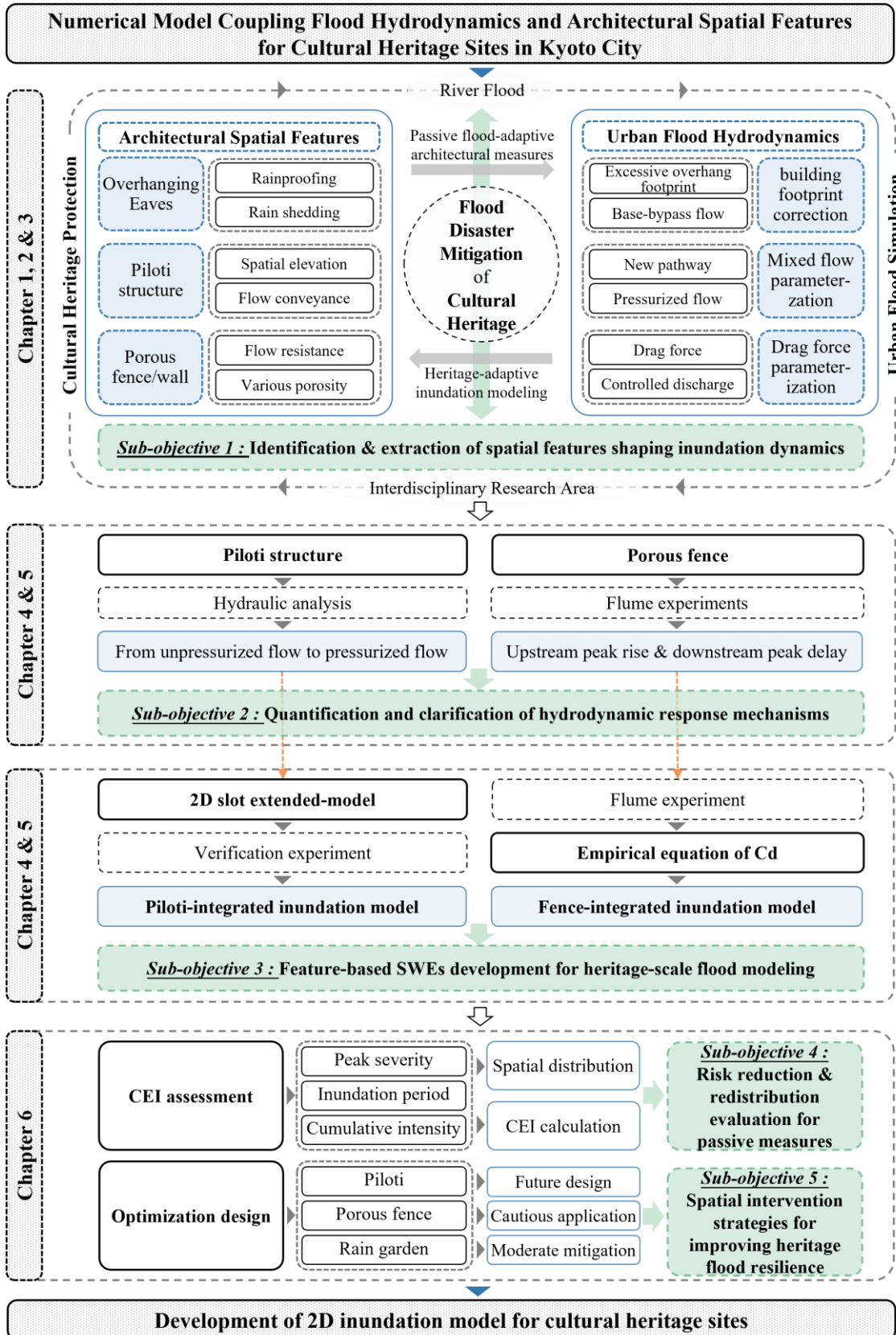


Figure 1.4 Research framework

2. Literature Review

2.1. Concepts and definitions

In relevant policy documents and academic research, terms such as “cultural heritage” “river floods” and “passive flood-adaptive architectural design” typically carry broad meanings encompassing diverse types and contexts. Given that this study focuses exclusively on urgent practical issues, this section provides concise definitions of core concepts to clarify research boundaries and avoid confusion with conventional usage.

2.1.1. Cultural heritage

According to the World Heritage Convention, cultural heritage primarily encompasses three categories: individual monuments and sites of outstanding universal value, groups of buildings, and cultural landscape sites (UNESCO World Heritage Centre, 1972). In Japan, the Law for the Protection of Cultural Property classifies cultural assets into tangible cultural properties, intangible cultural properties, folk cultural properties, monuments (historic sites, scenic spots, natural monuments), and cultural landscapes (Law No. 214 of 1950). Compared to movable cultural assets, immovable architectural and landscape heritage cannot be relocated or replaced as a whole. Damage from floods causes irreversible loss of value, making them the primary focus of this study. The term “cultural heritage sites” in this research primarily refers to immovable cultural assets in Kyoto City, particularly imperial palaces, shrines, temples, and their surrounding environments dominated by traditional architecture and gardens or landscapes.

Regarding conservation principles, the Nara Document on Authenticity explicitly states that “authenticity is the central element in defining, evaluating, and monitoring the value of cultural heritage,” requiring the preservation of authenticity and integrity in materials, design, craftsmanship, environment, and other aspects to the greatest extent possible (ICOMOS, 1994). Therefore, for architectural and garden heritage sites, enhancing flood prevention capabilities through large-scale demolition and reconstruction or visually intensive engineering measures is impractical. These further underscores the necessity of evaluating and optimizing flood mitigation performance

within the constraints of existing spatial layouts and structural conditions.

2.1.2. River floods

Generally speaking, river flooding refers to the process where rivers or streams experience rising water levels driven by heavy rainfall, snowmelt, or other factors, exceeding the channel's flood discharge capacity and overflowing the banks or levees, thereby inundating adjacent low-lying areas (IPCC, 2012). Compared to pluvial floods, which form directly on urban surfaces due to short-duration heavy rainfall, river floods more severely impact flood-prone areas along river corridors, floodplains, and downstream confluence zones. Given humanity's tendency to settle near water, urbanization and societal development footprints have grown along rivers (Mihu-Pintilie and Nicu, 2019). Consequently, many cultural heritage sites are located in flood-prone areas near rivers (Bernardini et al., 2021; Wang, 2015), suggesting that riverine historic built environments face particularly severe flood risks. This paper primarily examines potential river flood processes along Kyoto City's major rivers (the Kamo River and Katsura River).

2.1.3. Passive flood-adaptive architectural design

Passive flood-adaptive architectural design refers to architectural and urban design strategies that utilize spatial and structural features (such as elevated ground floors, porous fences, detention basins, and site/building layouts) to regulate local flood hydrodynamic flows. This approach reduces flood exposure and loss risks in critical spaces, enhancing their flood resilience. Compared to active measures, such designs function automatically during flooding (Mannucci et al., 2022). Their advantages include reduced reliance on human operation, electricity, and control systems, typically offering significant cost and energy savings. They also minimize the risk of measure failure due to deployment issues or malfunctions during sudden flood events, ensuring more stable performance (Peck et al., 2022). At the architectural design level, this approach emphasizes adapting to local environmental conditions, transforming flood control structures from external additions into integral parts of the spatial fabric. This creates distinctive, perceptible, and enduring architectural spatial features that harmonize

aesthetic appeal with regional expression. This design approach better integrates flexible materials and scales, offering greater visual appeal and reduced environmental impact compared to heavy, rigid defenses. Consequently, it enhances the acceptability of flood control measures within cultural landscapes and historical environments (Eggleston et al., 2021) . This method of embodying flood mitigation functions within architectural spatial forms creates an immediately comprehensible interdisciplinary connection point, providing a direct physical medium for the interdisciplinary research on hydraulics and architecture explored in this paper.

2.2. Previous studies and findings

2.2.1. Flood damage mechanisms in heritage buildings

Traditional structures mainly built from timber, rammed earth, and stone, are vulnerable to hydrodynamic pressures, buoyancy, and prolonged inundation during flooding, which could cause direct or indirect permanent damage by erosion, scouring, or mold growth (Blavier et al., 2023) . The impacts are mostly controlled by flood depth, flow velocity, and duration at the architectural scale. Therefore, a flood numerical model capable of analyzing local flow fields and outputting specific data is required to support decision-making (Fig. 2.1). This leads to the research interface addressing the interdisciplinary problem in this paper: the specific impact of floods on cultural heritage can be assessed using a flood numerical model that analyzes local flow fields and outputs specific data.

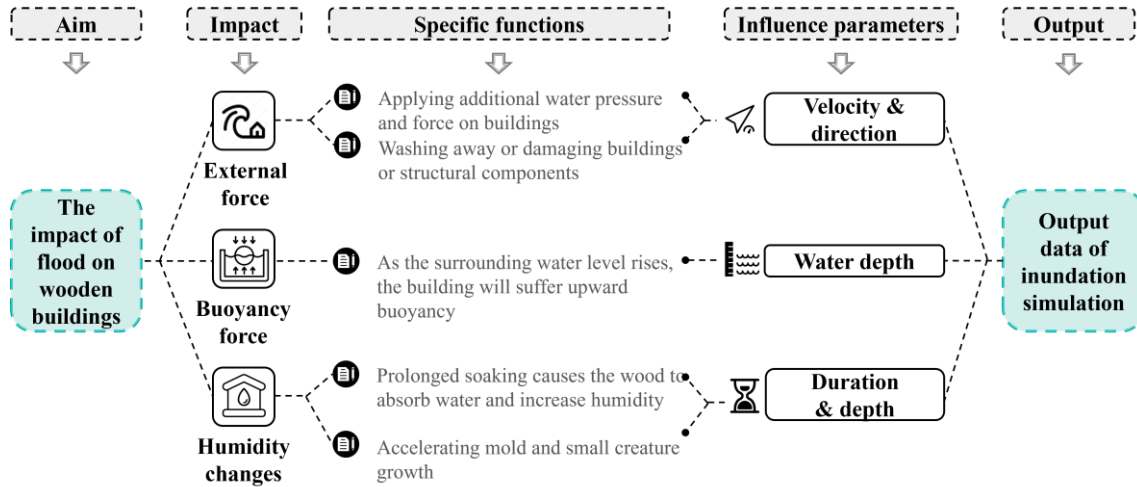


Figure 2.1 Impact of Flood on traditional wooden buildings

2.2.2. Flood hazard research in cultural heritage sites

The issue of flood disasters affecting cultural heritage has received increasing attention in recent years, though it remains a relatively minor concern. Existing research has largely focused on macro-level discussions such as risk assessment, vulnerability analysis, and resilience frameworks. Key findings primarily revolve around identifying which heritage sites are more vulnerable to flooding threats or which regions or assets deserve priority attention. Typical methodologies involve organizing flood hazard, exposure, and vulnerability into an assessment system, followed by spatial screening and prioritization. For instance, on the global scale, researchers have utilized global river flood hazard map. By overlaying World Heritage sites with their types and value attributes, they constructed risk matrices to identify high-risk heritage sites and regional distribution patterns (Arrighi, 2021; Kalogeropoulos et al., 2023). Other studies have evaluated large-scale flood risk maps for cultural heritage risk assessment, noting that assumptions regarding point-based heritage databases, terrain resolution, and hazard maps significantly influence risk determination (Lanza, 2003; Nobile et al., 2025). At regional and urban scales, related work often focuses on historic districts or heritage towns. Methods such as the index approach or AHP incorporate building materials, structural types, floor heights, underground spaces, and critical facilities into vulnerability assessments. These are then overlaid with hazard indicators like water depth and

inundation extent to form flood risk zoning (Ferreira and Santos, 2020; Salazar et al., 2024) . Although these studies have limited direct relevance to the present research, their contribution lies in providing a generalizable disaster assessment workflow suitable for rapidly locating, confirming risk zones, and establishing management priorities for a large number of widely distributed heritage sites. However, these studies share common limitations: the quantitative flood information supporting assessments still primarily relies on historical inundation records or macro-scale hazard maps, lacking high-precision dynamic flood behavior predictions. Consequently, existing studies have primarily conducted large-scale risk assessments at global or national scales, with limited research on the physical mechanisms of interaction between architectural features and hydrological environments. There is a lack of localized, high-resolution flood impact analysis applicable to cultural heritage sites, making it difficult to reveal the specific damage mechanisms and dynamic response behaviors of cultural heritage during floods. This represents an applied challenge in confronting the practical issue of heritage flood protection.

Highly aligned with the focus of this study, heritage management authorities at all levels increasingly emphasize identifying the magnitude, scope, and exposure of disasters threatening cultural heritage. They support disaster resilience design and management through risk assessments and hazard mapping (UNESCO et al., 2010; World Bank, 2015) . Within this trend, some studies have begun attempting to quantify the intensity of disasters affecting heritage using hydrological or hydrodynamic methods. At the heritage site or historic district scale, 2D hydrodynamic models are employed for hazard calculation, with water depth or flow velocity serving as primary hazard indicators. These are then overlaid with building or district vulnerability to generate risk outcomes (D'Ayala et al., 2020; Tamagnone et al., 2025) . However, these studies merely employ numerical models as existing research tools without incorporating heritage architectural characteristics into modeling parameters to enhance applicability at the heritage level. At the individual structure or artifact scale, existing work employs CFD methods to simulate flood flow around individual bridges, erosion, or hydrodynamic loads, revealing localized stresses and vulnerable points (Li et al., 2025). But this approach remains confined to

single heritage elements, neglecting the interaction between structures and their sites, and thus struggles to be directly generalized to other heritage projects with broader applicability.

Existing research has matured in risk frameworks and assessment processes, gradually incorporating hydrodynamic simulations to provide hazard input data. However, at the heritage site scale, studies capable of refining inundation dynamics simulations and integrating spatial heritage features that directly influence flood behavior into model parameters remain relatively underdeveloped. Consequently, it remains challenging to quantitatively explain the coupled relationships between flood intensity, reach extent, exposure patterns, and spatial heritage configurations at heritage sites. Subsequent sections should further explore the mechanisms by which heritage spatial features influence local hydrodynamic processes, along with their advantages, limitations, and applicability in flood mitigation. Overall, this field urgently requires a modeling approach that can directly incorporate and effectively represent architectural spatial features within 2D hydrodynamic models, enabling heritage-scale flood simulations tailored to building clusters and their surrounding environments.

2.2.3. Representation of architectural features in flood modelling

A key approach for non-structural flood risk management measures involves utilizing hydrodynamic modeling for dynamic simulation to obtain hazard data (Ahmadisharaf et al., 2018; Alipour et al., 2022; Dewals et al., 2023; Ghostine et al., 2015; Kumar et al., 2023; Mondal et al., 2025; Patel et al., 2017, 2017; Wu et al., 2017) . Hydrodynamic models based on the 2D shallow water equations (SWEs) represent a mature hydrological research approach with several distinct advantages over alternative methods such as remote sensing and historical disaster data collection: 1). They can generate complete, high-precision spatiotemporal distributions; 2). capable of simulating multiple scenario conditions; 3). Simultaneous output of various dynamic hazard indicators (water depth, flow velocity, duration, inundation extent, etc.)(Guo et al., 2021; Xia et al., 2017) . Simulation results are primarily controlled by factors such as DEM data, land use, rainfall or upstream inflow, roughness coefficient, and grid resolution to obtain

data on flow velocity, water depth, and flood duration (Alipour et al., 2022; Anik et al., 2025; Thomas Steven Savage et al., 2016).

However, in heritage contexts, traditional hydrodynamic models exhibit insufficient precision in representing architectural spatial features. When applied to localized flood simulations at heritage sites, this leads to considerable errors. Within the hydraulic field, such models are predominantly used at large scales like urban areas or river basins, where buildings are typically represented through various generalization methods. These include increasing roughness parameters (Gallegos et al., 2009; Gallien et al., 2011; Liang et al., 2007), representing the obstacles as holes in the mesh (Aronica and Lanza, 2005; Schubert et al., 2008), or employing porosity-based models (Bruwier et al., 2017; Chen et al., 2012; Ferrari and Viero, 2020; Guinot et al., 2017; Kawaike et al., 2022; Kim et al., 2015; Sanders et al., 2008). The above methods are primarily applied to river flooding scenarios. For direct rainfall events, building heights are often approximated using high-resolution elevation data (Brown et al., 2007; Glenis et al., 2018; Hunter et al., 2008; Schubert et al., 2008). These approaches do not significantly impact large-scale scenarios like urban flooding, representing a reasonable simplification that enhances simulation efficiency and application convenience by avoiding unnecessary detail. However, when addressing localized flooding at the building cluster scale, such as in cultural heritage sites, modeling considerations require greater refinement.

In fact, at the complex scale, many key heritage architectural features (such as piloti, porous fences, and overhanging eaves) intervene in flood flow processes by disrupting water movement. This is precisely where passive flood-adaptive architectural design comes into action. The transitional generalization of architectural spatial features in the model introduces non-negligible errors in flood flow simulations, leading to either overestimation or underestimation of flood intensity at the building level. Developing hydrodynamic models suitable for cultural heritage flood simulation necessitates incorporating key heritage features that directly influence flood flow into complex hydrodynamic processes. This is crucial for achieving high-precision flood simulation at the building complex scale. However, existing hydrodynamic research has yet to address this practical issue, exposing methodological limitations in applying hydrodynamic

modeling to heritage architectural contexts.

2.2.4. Effectiveness assessment of passive flood-adaptive measures

Many cultural heritage sites still retain passive flood-adaptive architectural designs developed through long-term coexistence with flood-prone environments, which often become defining spatial features of key heritage structures (e.g., piloti, elevated foundations, fences, courtyard drainage systems). One crucial factor enabling these heritage buildings to endure for millennia is the enduring value of traditional wisdom embodied in such passive measures, which warrant significant research and contemporary adaptation. However, existing discussions often remain confined to empirical descriptions of their flood mitigation efficacy, lacking clear explanations of mitigation mechanisms and potential side effects. Early research has emphasized the need for comparative evaluation criteria when selecting among different combinations of measures. For instance, economic efficiency criteria, such as minimizing flood damage losses and engineering or flood protection reinforcement costs, can be used to compare combinations of structural and non-structural measures (James, 1965) . It is important to distinguish that evaluating measure effectiveness is not entirely equivalent to risk or vulnerability assessment. The former focuses on the relative change in hazards or losses before and after implementing measures under the same flood scenario to quantify the contribution of the measures (Pudar et al., 2020; Schanze et al., 2008)。

Regarding the evaluation of flood mitigation measures' effectiveness, existing research primarily focuses on three approaches: The first is an evaluation based on physical damage factors, relying on hydrological and hydraulic models or other computational methods to generate indicators such as water depth, flow velocity, and inundation duration. This approach compares changes in flood intensity or the flood process before and after the implementation of measures (Schanze et al., 2008) . The second approach is based on economic benefits, converting the effects of measures into gains or losses, followed by cost-benefit comparisons (James, 1965; Pudar et al., 2020) . The third approach is a composite evaluation, which constructs multidimensional technical, social, and environmental indicators to support scheme selection. Typically,

human impacts from flooding are quantified through indicators such as water depth, flow velocity, and inundation duration, forming an evaluation framework alongside environmental, social, and technical dimensions (Bana E Costa et al., 2004) . Social impacts are further specified through metrics like evacuation events and psychological stress (Simonovic, 1999)。

However, the previously mentioned evaluation approach demonstrates significant misalignment within the cultural heritage context. First, the historical and cultural value of cultural heritage is difficult to assess conventionally (Schanze et al., 2008) , making it challenging to incorporate economic benefit evaluations into the assessment framework. Second, heritage conservation objectives are not equivalent to a statistical value of minimizing expected losses. Instead, they emphasize the spatial distribution of key components' exposure and damage expectations, as well as the distribution and potential migration relationships of disasters across different levels of architecture and environment. Consequently, evaluations must account for the distribution of various flood intensity indicators across two-dimensional space and their dynamic changes over time, rather than relying on a single numerical summary. For these reasons, a more suitable effectiveness evaluation framework at the heritage site scale is needed. This framework should characterize disaster mitigation benefits using physical hydrodynamic indicators while accounting for differentiated effects and evaluations at both the architectural level and the landscape or environmental level.

2.2.5. Flood resilience strategies for heritage sites

As extreme rainfall intensifies and flood discharge conditions change due to human activities such as land use and river channel management, passive adaptation designs developed under traditional environmental conditions may no longer reliably cope well with current and future flood scenarios (Blöschl, 2022) . Therefore, optimizing flood resilience measures for heritage sites in response to new environmental contexts holds significant importance for the preservation and development of cultural heritage.

The selection of flood mitigation measures for cultural heritage sites is primarily governed by conservation principles. The fundamental principles for safeguarding World

Heritage and significant cultural heritage include preserving authenticity and integrity, alongside principles of minimal intervention and reversibility (ICOMOS, 2017, 1994) . This implies that the form, materials, and landscape patterns of the heritage entity itself cannot be easily altered, making large-scale rigid flood control projects like new embankments or high walls difficult to accept (Feilden, 2007) . Furthermore, heritage management authorities generally emphasize a risk management approach encompassing pre-disaster preparedness, emergency response during disasters, and post-disaster recovery, requiring integration into the existing management systems of heritage sites (UNESCO et al., 2010; World Bank, 2015). Under these dual premises, flood response strategies in heritage sites typically prioritize management measures while exercising caution with engineering interventions. This approach aims to minimize alterations to the heritage entity and landscape character, confining engineering measures to reversible, maintainable, and landscape-compatible solutions.

From the perspective of specific measure types, existing research can be categorized into two main groups: The first group focuses on core management practices, including risk assessment and zoning, resource allocation, monitoring and early warning systems, emergency response plans, evacuation procedures, and response coordination. These measures often leverage flood risk assessment outcomes to prioritize heritage management actions (Coombes and Viles, 2021; Figueiredo et al., 2020) . This approach most easily aligns with the general requirement for low intervention in heritage protection but cannot directly mitigate disasters. The second category involves structural measures centered on engineering or spatial modifications, such as proposals to restore existing underground reservoirs in ancient cities (Lanza, 2003) , though empirical studies on actual implementation remain scarce. Engineering interventions face multiple constraints at heritage sites, often taking temporary, reversible, or low-impact forms. Another critical consideration when adding measures is the relationship between the overall spatial configuration of heritage sites and the localized layout of interventions, which directly impacts flood mitigation effects and potential risk redistribution. Therefore, numerical modeling to optimize solutions is vital for supporting comparative analysis and benefit-cost tradeoffs, thereby enhancing resilience at heritage sites.

2.3. Limitations of previous study

Based on the above research review, under the dual considerations of heritage conservation restrictions and flood mitigation requirements, flood management at cultural heritage sites increasingly presents the following new demands:

1) Heritage conservation places greater emphasis on flood intensity and inundation process parameters at the scale of buildings and critical structural components (such as water depth, flow velocity, duration, and inundation extent), as these directly determine the conditions under which heritage structures sustain damage. However, existing quantitative flood data supporting heritage decisions primarily rely on historical records or macro-scale hazard maps, which struggle to resolve local water depth and flow field variations within heritage sites. This leads to the first requirement: acquiring building-scale flood intensity information tailored to heritage flood protection challenges.

2) As a well-established flood simulation tool, two-dimensional (2D) hydrodynamic modeling has been widely applied to urban flooding and large-scale inundation analysis. However, for small-scale inundation processes within heritage sites, the spatial characteristics of buildings, which directly influence flood dynamics, play a significant role yet remain largely unaccounted for in modeling. This highlights a second requirement: developing a 2D hydrodynamic model that incorporates key architectural spatial features.

3) Passive flood adaptation designs within heritage sites hold significant learning and translation value. However, discussions of these measures in heritage contexts often rely on qualitative descriptions or general principles, lacking clear understanding of their hydrodynamic regulation mechanisms and effect evaluations. This makes it difficult to support the detailed assessments and scheme comparisons required for resilient optimization design. The third requirement thus emerges: to construct a comprehensive performance evaluation system applicable to heritage sites, providing quantitative support for the design rationale and applicability boundaries of passive measures.

Based on these needs and focused on heritage architectural contexts, this paper aims to translate architectural spatial features directly influencing flood behavior into computable hydrodynamic parameters. It establishes a 2D inundation model applicable

to cultural heritage sites to enable detailed flood simulation, supporting the identification of critical exposed spaces and damage assessment. Additionally, it will analyze the hydrodynamic regulation mechanisms of traditional measures, quantify and evaluate their flood mitigation effectiveness and potential side effects, thereby providing design guidelines for resilient optimization.

3. Methodology

3.1. Study area

The Kyoto Basin lies in the middle reaches of the Yodo River system, traversed by multiple rivers including the Katsura, Kamo, and Uji Rivers. River flooding consistently ranked among the most impactful natural disasters, causing significant damage to riverside areas. The Kamo and Katsura Rivers, due to their unique locations flowing through the historic city center, have become primary subjects of concern regarding river flooding issues. This study focuses specifically on river flooding, selecting Shimogamo Shrine and Katsura Imperial Villa as case studies. Both are situated adjacent to Kyoto's major rivers (the Kamo and Katsura Rivers). Katsura Imperial Villa, a royal property located on the right bank of the Katsura River in Kyoto's Nishikyo Ward, comprises 17th-century imperial residences and a pond-centered stroll garden, featuring a more clearly defined landscape spatial sequence. The garden features interconnected water surfaces, bamboo fences, and traditional wooden structures partially elevated off the ground. Shimogamo Shrine, situated at the confluence of the Kamo and Takano Rivers in northern Kyoto City, is a vital component of the “Cultural Properties of the Ancient Capital Kyoto.” The shrine's compact complex forms an enclosed courtyard spatial layout. Both sites are situated along riverbanks in low-lying areas, designated as areas with high flood risk on Kyoto City's flood hazard map (Fig. 3.1), demonstrating the urgency and representativeness of this research topic. This study selects Katsura Imperial Villa and Shimogamo Shrine as two representative research subjects within Kyoto City's cultural heritage sites. It analyzes the impact of their shared heritage spatial characteristics on local hydrodynamic processes and flood risk, as well as the differences in hydrodynamic responses resulting from their distinct spatial layouts.

One notable issue is that, based on Kyoto City's flood records, the areas surrounding the Kamo and Katsura Rivers have experienced multiple instances of severe flooding. It is presumed that the Shimogamo Shrine and Katsura Imperial Villa would inevitably have been affected (Kawasaki et al., 2013). However, formal documentation regarding the damage sustained by cultural heritage sites is extremely limited, and no specific data

exists (Table 3.1). On one hand, this may reflect incomplete disaster documentation in heritage historical records; on the other, it is more likely attributed to traditional flood prevention measures incorporated during the design and construction phases of these sites (e.g., elevated ground floors, porous fences) (Kawasaki et al., 2013) . Nevertheless, these conclusions currently remain largely qualitative. With contemporary urban expansion, changes in land use types, and the advancement of river channel regulation and embankment construction, local flood discharge conditions and potential water flow paths now differ significantly from historical periods. What flood response mechanisms are hidden within the original flood mitigation measures of traditional heritage sites? Are these flood defense patterns still applicable? How can the flood resilience of contemporary heritage sites be further enhanced? These questions all point to the importance of conducting further research through quantitative hydrodynamic analysis and scenario simulation.

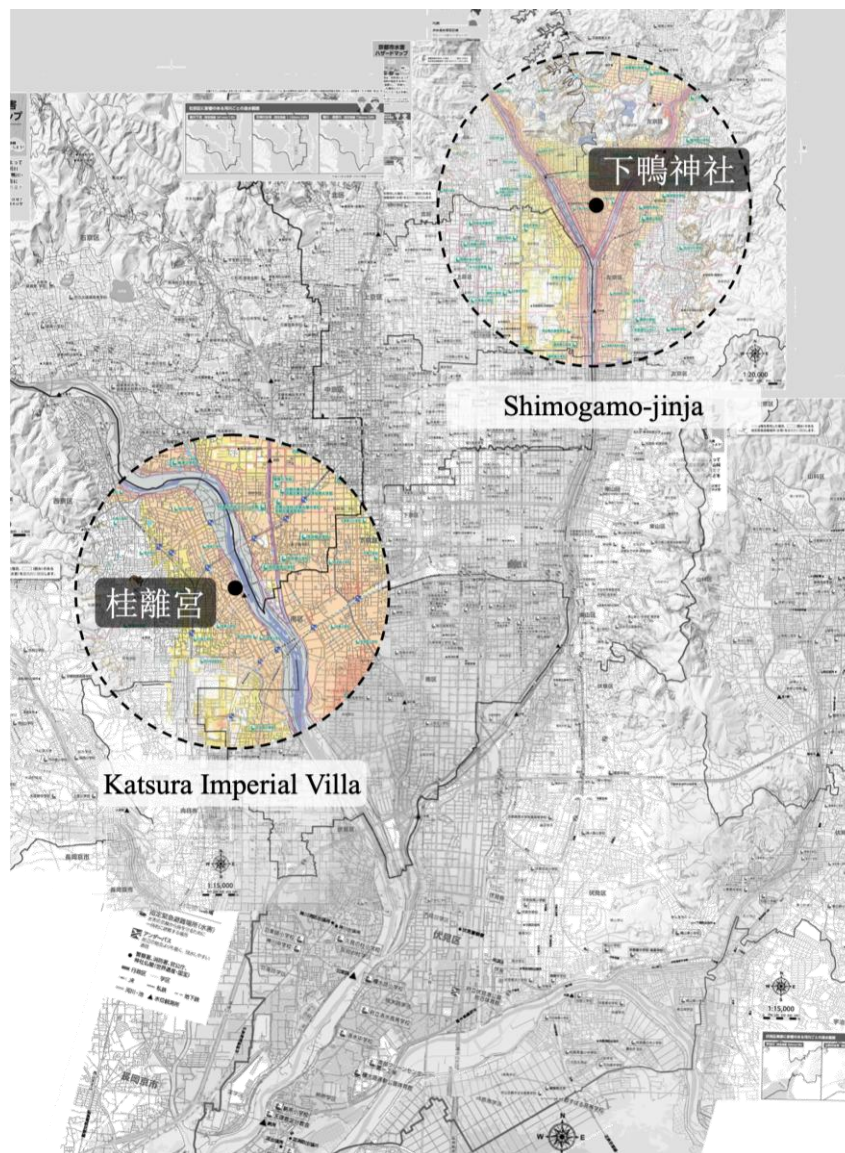


Figure 3.1 Main heritage sites beside the rivers
(source: <https://www.bousai.city.kyoto.lg.jp/>)

Table 3.1 The Flood Disaster of Main Cultural Heritage

Name	Classify	Time	Flood Condition
Shimogamo-Jinja	World Cultural Heritage	1935	Affected (No detailed data)
Katsura-Rikyu	Royal property	1644	書院&松琴亭 have been destroyed
		1903	The water inside reached the same height with inner floor of 松琴亭.

3.2. Architectural typology

In the first step of this study, we introduced typological methods from architecture to systematically categorize the architectural and spatial features of Kyoto's major cultural heritage sites, particularly those distinguishing them from typical urban built areas. The research subjects encompassed representative heritage sites in Kyoto (Fig. 1.3a), with reference materials including historical drawings, field surveys, and photographs. We then identified spatial elements directly influencing flood hydrodynamic behavior. Aligning with subsequent hydrodynamic modeling and analysis requirements, this typological approach identified three key spatial elements: overhanging eaves, ground-level elevated structures (piloti), and fences with varying porosity (Fig. 3.2). The subsequent research objective is to translate these spatial prototypes into parameterized terms that can be incorporated into hydrodynamic models: using slot-extended model to characterize piloti effects, and adding resistance terms to represent different wall and hedge types, thereby enabling the conversion of architectural features into hydrodynamic responses.

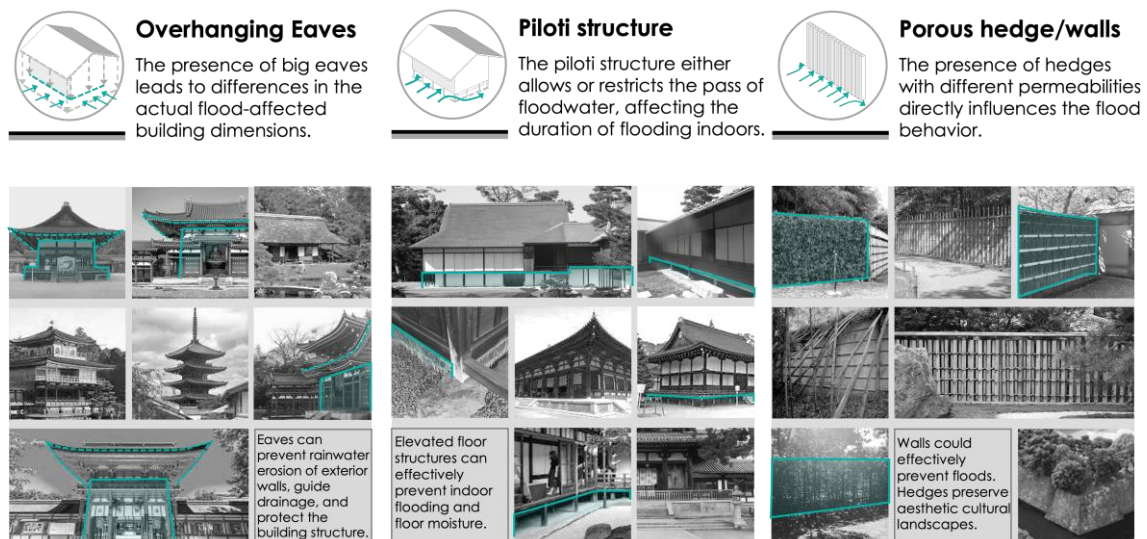


Figure 3.2 Extraction of spatial characteristics that influence flood behaviors

3.3. Numerical modeling

Based on the preceding discussion, in order to obtain flood dynamics data for the

flood process within the heritage building area, this study employs a 2D flood hydrodynamic model as the foundational research tool and further develops it. Initially, the original flood model was a 2D urban surface flood model based on the 2D shallow water equations (SWEs) (Kawaike, 2002). An unstructured mesh is employed within the model, ensuring its flexibility and accuracy in capturing building footprints within complex urban areas, especially for the heritage site in this study. The basic model has been extensively applied in prior studies, demonstrating its effectiveness and reliability for urban inundation simulations (Lee et al., 2016; Noh et al., 2018, 2016; Zheng et al., 2024; Zhu et al., 2025). The governing equations are as follows:

Continuity equation:

$$\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \quad (1)$$

Momentum equation:

$$\frac{\partial M}{\partial t} + \frac{\partial(uM)}{\partial x} + \frac{\partial(vM)}{\partial y} = -gh \frac{\partial H}{\partial x} - \frac{gn^2 M \sqrt{u^2 + v^2}}{h^{4/3}} \quad (2)$$

$$\frac{\partial N}{\partial t} + \frac{\partial(uN)}{\partial x} + \frac{\partial(vN)}{\partial y} = -gh \frac{\partial H}{\partial y} - \frac{gn^2 N \sqrt{u^2 + v^2}}{h^{4/3}} \quad (3)$$

where h denote the water depth; H is the water level; g means the gravity acceleration; n means Manning's roughness coefficient; u , v are the x , y directional velocity, respectively; $M(= uh)$, $N(= vh)$ represent the x , y directional flow flux, respectively. The study involves multiple evaluations of model performance, which can be assessed using Root Mean Square Error (RMSE) and Nash-Sutcliffe efficiency (NSE). The calculation formulas are given in Eq. (4) and Eq. (5):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (Q_{exp,i} - Q_{sim,i})^2} \quad (4)$$

$$NSE = 1 - \frac{\sum_{i=1}^n (Q_{exp,i} - Q_{sim,i})^2}{\sum_{i=1}^n (Q_{exp,i} - \bar{Q}_{exp})^2} \quad (5)$$

Here, $Q_{exp,i}$ denotes the experimental observation data at point i , $Q_{sim,i}$ represents the corresponding model simulation data, $\bar{Q}_{exp}$ is the average of all observation data, and n is the total sample size. After validation, the slot-extended model can be applied to comparative inundation scenarios in real-world cases.

3.4. Laboratory experiments

To validate the applicability of numerical models or explore the hydrodynamic mechanisms of spatial elements, this study conducted a series of physical model experiments at the Ujigawa Open Laboratory of Kyoto University. All experiments were performed in a rectangular flume measuring 1 m wide and 20 m long, with side walls and bottom primarily constructed of glass. Flow in the upstream section of the open channel was controlled by a variable-frequency pump, while the downstream section maintained an open boundary allowing free outflow (Fig. 3.3). Key measured data included flow rate and water depth. Flow rate was obtained via an electromagnetic flowmeter installed on the upstream inlet pipe, with a precision of 0.01 L/s. Water depth was measured using ultrasonic sensors set to a measurement interval of 200 μ s. Chapters 4 and 5 designed specific test conditions for different types of traditional flood control measures (e.g., piloti, porous walls). The instrumentation configuration remained consistent across all test conditions. Detailed experimental protocols and variable settings will be elaborated in subsequent chapters.

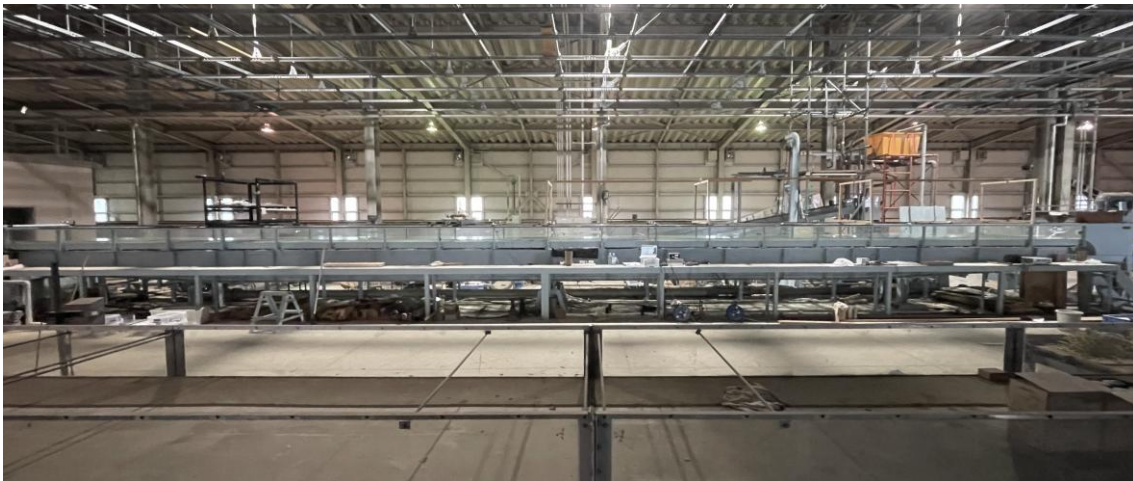


Figure 3.3 The image of experimental flume

3.5. Comprehensive effectiveness index

Existing research still lacks a systematic characterization of the operational mechanisms underlying traditional flood mitigation measures, and methods for evaluating

their effectiveness remain notably underdeveloped. To quantitatively assess the flood reduction efficacy of traditional flood mitigation measures in cultural heritage areas, this study developed a Comprehensive Effectiveness Index (CEI) based on multiple indicators. This evaluation system categorizes assessment targets into two hierarchical levels: “protection effectiveness of the cultural heritage entity” and “hydrodynamic impact on surrounding sites.” This approach comprehensively reflects the risk reallocation effects induced by flood mitigation measures. By normalizing and weighing multiple hydraulic indicators, including water depth, inundation duration, and cumulative exposure, the system generates a dimensionless composite index suitable for horizontal comparison across different measures and scenarios. Given the extremely slow overall flow velocity at the cultural heritage sites studied, where directly related external forces and scouring risks are relatively insignificant, the current CEI framework does not consider disaster effects caused by flow velocity. However, in future scenarios where flow velocity changes are prominent or significant hydrodynamic impact risks exist, indicators related to flow velocity should be incorporated as key evaluation metrics within this framework. The complete methodology for indicator selection, calculation steps, weighting assignment, and detailed calculation methods will be elaborated in Chapter 6 of this paper.

3.6. Data sources and preprocessing

3.6.1. Basic data

The data collection and preprocessing supporting numerical simulation are divided into the following steps: (i) utilizing the 5-meter resolution DEM data (December 2023 edition) from Japan's Ministry of Land, Infrastructure, Transport and Tourism (<https://www.gsi.go.jp/kiban/>, last accessed Nov., 2025), which would be used as basic elevation data later; (ii) simulated map data also sourced from MLIT, used to distinguish land use types and serve as the foundational reference for boundaries of various land categories; (iii) the piloti heights for the main buildings were determined through atlas references or field measurements; (iv) the simulated breach points and inflow discharge were determined by referencing Japan's official Flood Hazard Map

(<https://suiboumap.gsi.go.jp/ShinsuiMap/>, last accessed Nov., 2025). Among nearer hypothetical breach points near the site, the one with the greatest impact on the target heritage area was selected. The inflow condition was set using the back calculated from the assumed maximum flood event (approximately 1/1000). All boundaries of the simulation area were set as open boundaries; (v) considering the possibility of minor water leakage through door and window gaps, the building was set as semi-transparent, with an exchange rate of 0.01 relative to other meshes (Akoh et al., 2015)。

3.6.2. DEM interpolation

Elevation data obtained from Japan's MLIT online platform has a maximum accuracy of 5m within the study area. However, as this research focuses on the architectural scale, where many building components measure less than 1m, and considering that deviations in shoreline features like ponds in low-lying areas can cause significant errors in simulating waterfront buildings, using 5m-accuracy elevation data would inevitably compromise simulation precision. To achieve higher-precision terrain representation at the architectural scale, this study attempted to re-extract the existing 5m-precision terrain data into 1m-precision elevation data. This process employed two interpolation methods built into QGIS software: Triangulated Irregular Network (TIN) and Inverse Distance Weighted (IDW). The fundamental approach of TIN interpolation involves constructing an irregular triangular network from isolated elevation points and performing planar interpolation within each triangle. IDW, conversely, calculates a weighted average based on the principle that nearer samples carry greater weight. Comparing results from different interpolation methods in the Katsura Imperial Villa, Figure 3.4 illustrates that the TIN method better aligns with the original shoreline and produces smoother data. In contrast, IDW accentuates elevation changes and fits the shoreline less effectively than TIN. The degree of shoreline fit directly represents the elevation resampling quality in low-lying areas. Therefore, the TIN method is adopted for interpolation in this study.

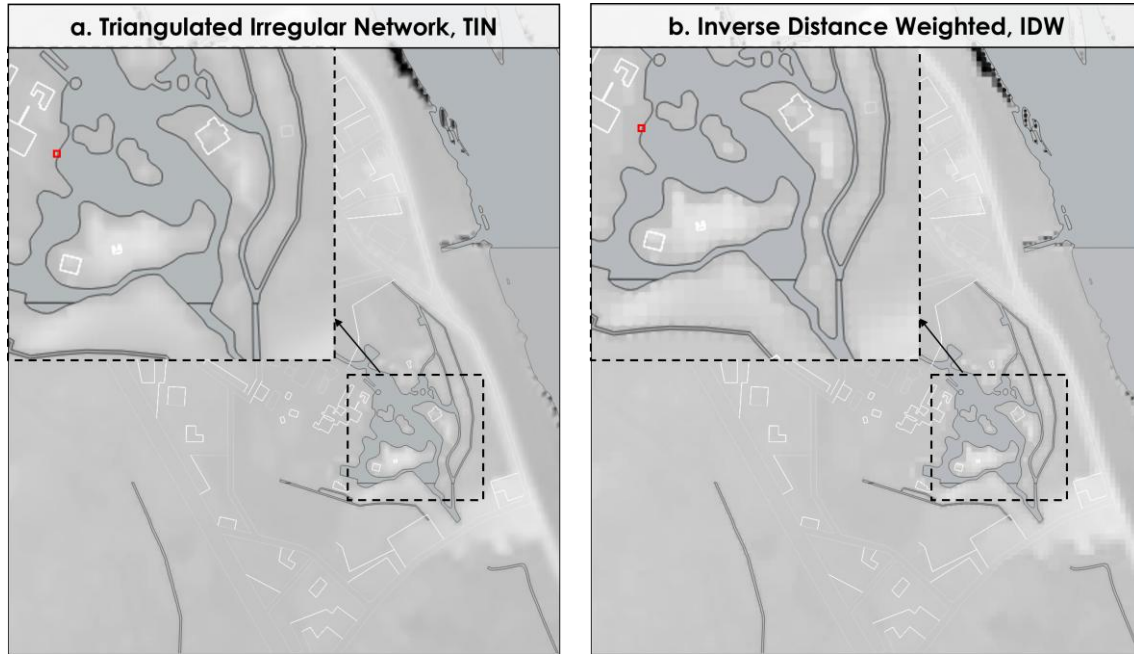


Figure 3.4 The DEM interpolation through TIN and IDW in Katsura-Rikyu

3.6.3. Building footprint refinement

Similar to Section 3.6.2, insufficient accuracy in building-scale plan data directly impacts the effectiveness of building-scale numerical simulations. Errors primarily derive from common inundation models directly utilizing satellite- or aircraft-derived two-dimensional map data. While neglecting fine details may not significantly affect large-scale simulations, local simulations are directly compromised by factors such as building footprints obscured by overhanging eaves or vertical obstacles like walls that satellite imagery cannot capture. Therefore, correcting base map data is crucial for heritage site simulations. However, obtaining accurate footprint data for different building types remains challenging, due to disciplinary barriers as well as access restrictions stemming from confidentiality and security requirements. This study employs field surveys and mapping, supplemented by historical drawings from reference collections (Nishikawa, 1982; Nishimura, 1879; Okamoto, 1982; Watanabe, 1984) , to manually correct vertical obstacles like walls and the floor plans of primary structures. This ensures the authenticity of the flood impact zone around buildings. Figure 3.5 illustrates the divergence between roof outlines and actual building footprints using the main structure of Katsura Imperial Villa as an example. Traditional wooden structures typically feature overhanging eaves

and projecting corridors. Using roof outlines as building boundaries would significantly overestimate the structures' ability to block surface runoff. Therefore, it is essential to revise the baseline building footprint data prior to simulation.

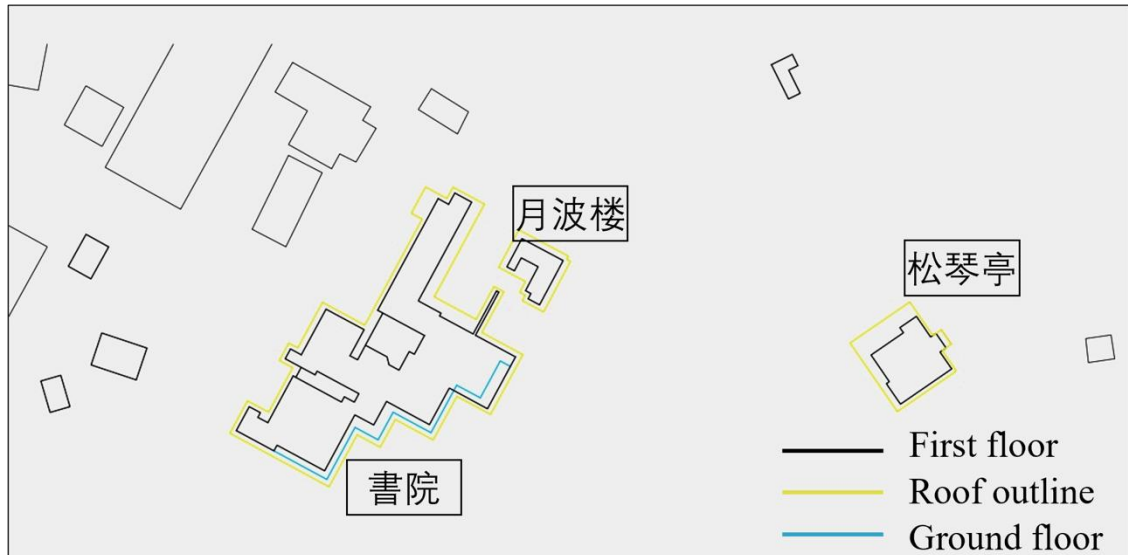


Figure 3.5 The refining of building footprints in Katsura-Rikyu

4. Modeling Extension and Validation of Piloti

The term “piloti” originates from French. It refers to a type of architecture where the ground floor is elevated and supported by columns (Liao et al., 2016), often called stilted or elevated buildings. First proposed by the renowned French architect Le Corbusier, this concept was widely promoted and applied within his modernist architectural theory. By elevating structures, the ground floor space is freed up, allowing wind, water, and people to pass through freely. This reduces the impact of floods, storm surges, or other natural disasters on buildings. Such design not only enhances structural safety but also provides additional public space or parking facilities.

In Japan, piloti functions both as a significant heritage element and a flood-adaptive design, especially in Katsura Imperial Villa (Kawasaki et al., 2013) . It lets floodwaters flow under the structures while raising the effective habitable floor level, which lowers the risk of flooding (Okubo, 2016). As a traditional passive flood mitigation design measure, piloti have been widely adopted in flood-prone areas globally since ancient times not only in Japan. Examples include the World Heritage sites Prehistoric pile dwellings around the Alps, the “Gabbiani” pile dwelling, as well as traditional dwellings in flood-prone regions of the United States, Australia, China (Lu and Zhang, 2021), Vietnam (Liao et al., 2016; Pasquier et al., 2024) , Nepal (Bodach et al., 2014) , the Philippines, India, and elsewhere. These structures employ piloti to enhance airflow and alleviate flood impacts (Liao et al., 2016; Pasquier et al., 2024). Raising the foundation level of buildings can significantly reduce flood risks has been a fact be widely accepted as conventional wisdom. (Han et al., 2024). In the context of modern historic district revitalization and waterfront development, piloti serve as disaster mitigation strategies that combine design aesthetics with spatial resilience. In France, the UK, and the US, regulations requiring coastal residences to incorporate elevated floors above designated flood levels have been part of the flood risk management framework for decades (Moeini et al., 2023; Pasquier et al., 2024). In Singapore, piloti spaces in collective housing often function as communal activity areas (Liao et al., 2016).

Regarding mechanisms and effectiveness, existing research on piloti is insufficient for dealing with their heritage preservation and contemporary application requirements.

Recent study on piloti has concentrated on numerical simulations under coastal wave conditions (Amini and Memari, 2024; Moeini et al., 2023) and physical experiments (Alam et al., 2023; Krautwald et al., 2022). A greater number of studies have focused on the impact of piloti on wind conditions and thermal comfort (Ibrahim et al., 2024; Kumar et al., 2021). Research on the interaction between flooding and piloti structures remains limited: Mitomi (2023) employed the SPH method to construct an idealized block, comparing flow velocity distributions within the block and changes in hydraulic pressure on downstream buildings under varying numbers and configurations of piloti structures. Results indicate that continuous or large-scale piloti building belts may partially reduce the pressurized area of some structures but could retain or even concentrate flood momentum, subjecting downstream buildings to higher peak water pressures. This suggests piloti structures possess potential negative impacts downstream. Ochiai & Jobe (2024) used Google Street View and field surveys to catalog over 500 piloti buildings along the Kuma River and its tributaries in Hitoyoshi City, Kumamoto Prefecture, demonstrating that piloti have become a significant residential adaptation measure in riverside urban areas. However, previous studies either focused on numerical experiments in idealized neighborhoods or addressed the qualitative phenomena and causes of piloti existence, lacking analyses of local flow fields and flood mitigation mechanisms using 2D hydrodynamic modeling methods.

This paper develops a flood adaptation model applicable to heritage buildings of the piloti type, focusing on their typical structural characteristics. First, the Pressman Slot model theory (Chaudhry, 2014) is introduced to express the hydrodynamic pressurization mechanism in the elevated floor space, constructing an enhanced 2D hydrodynamic model. Second, the effectiveness of the model's core innovative components is validated through controlled steady-state and unsteady-state flow flume experiments. Finally, applying the improved model to flood simulations at the Shimogamo Shrine and Katsura Imperial Villa, we obtained key parameters including inundation depth, flow velocity, inundation extent, and duration. Comparisons with unmodified simulations demonstrate the necessity of the expanded model and clarify the flood mitigation mechanism of piloti. Figure 4.1 illustrates the three main steps of this chapter's research:

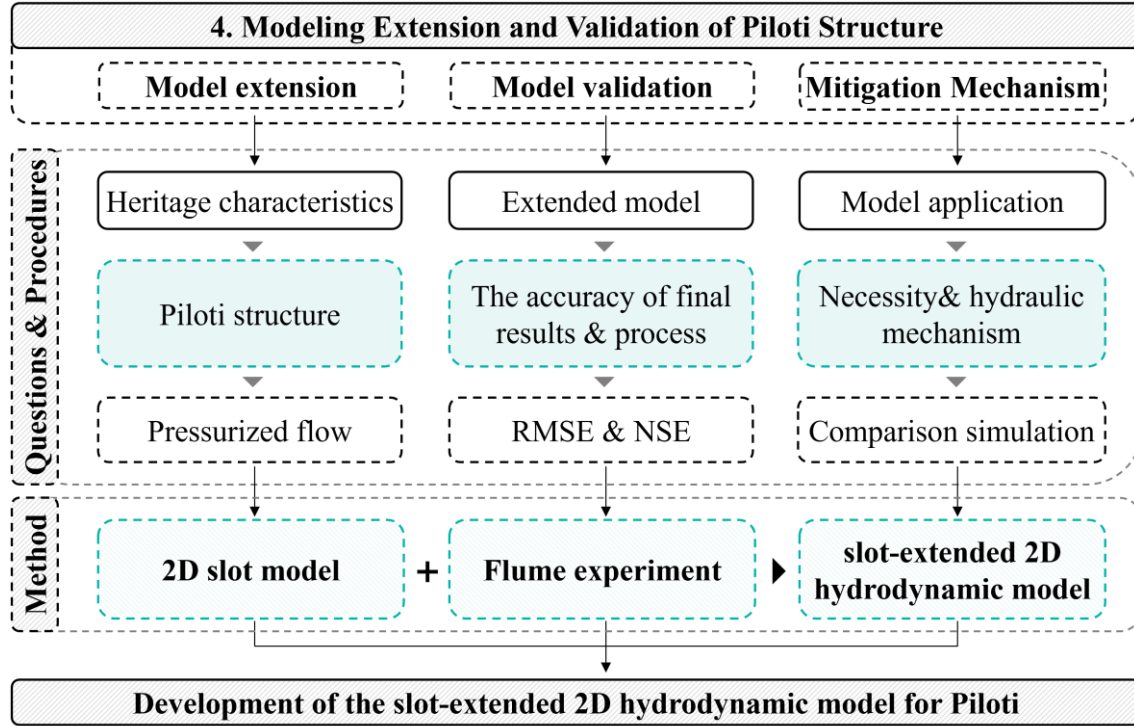


Figure 4.1 Research framework of Chapter 4

4.1. Hydraulic performance of piloti structure

4.1.1. The mixed flow under piloti structure

The presence of piloti structures alters the movement of water flow compared to conventional buildings. Although the space beneath the elevated floor is often enclosed by fragments such as columns, shear walls, and railings, water can still flow directly through the open area beneath the structure rather than around it. This creates entirely different water pathways (Fig. 4.2). The interaction between piloti and floodwater can be described as follows: When the water depth is beneath the height of piloti, inflow can directly pass through the elevated area; as the water depth rises above the elevated level, the piloti space gets inundated, transitioning from unpressurized to pressurized flow and showing a mixed flow condition. In particular, once the underfloor space becomes fully filled, the free surface locally disappears, and the flow behaves as a pressurized conduit-like flow. This pressurization can induce a local head buildup and alter the velocity distribution beneath the structure. Since classical 2D SWEs are formulated for free-

surface conditions and cannot describe pressurized states, the mixed flow problem should be handled by 2D Slot-Extended SWE.

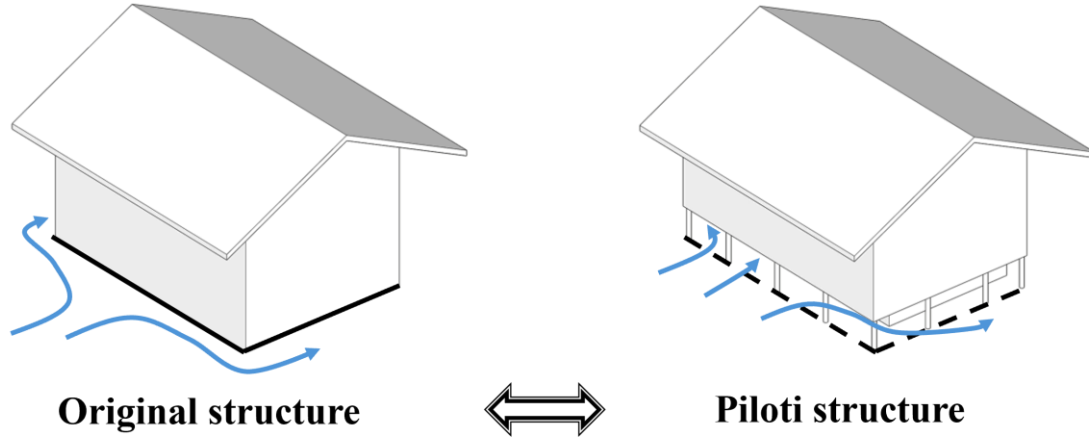


Figure 4.2 Diagram of piloti structure

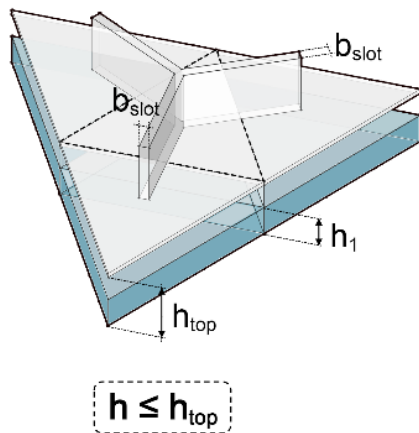
4.1.2. Developing slot-extended 2D hydrodynamic model

The fundamental approach to handling mixed flow involves connecting two sets of different governing equations at the interface between unpressurized and pressurized flow to achieve mixed flow treatment. However, this method is operationally complex and has low simulation efficiency. Since single-equation models are the simplest to use, the Preissmann Slot technique has become a widely adopted mature method. The classic Preissmann slot concept assumes an extremely narrow slot at the conduit top. Under additional flow conditions, this slot induces a virtual pressure head entering the slot, enabling mixed flow simulation with a single set of governing equations (Chaudhry, 2014; Cunge and Wegner, 1964). This method focuses on the transient transition from free flow to pressurized flow and is frequently applied to simulate pressurized water flow in urban underground pipe networks. As an extension, Maranzoni (2015) expanded the classical Preissmann slot model into a two-dimensional equation form, significantly broadening its applicability to hydraulic structures such as bridges or culverts. However, this two-dimensional extension relies on a constructed grid. In built-up areas, particularly complex heritage sites featuring piloti structures, the challenge of simulating mixed flow remains unresolved. This study introduces a novel slot-extended 2D hydrodynamic model for unstructured grids. This approach enables more precise representation of building

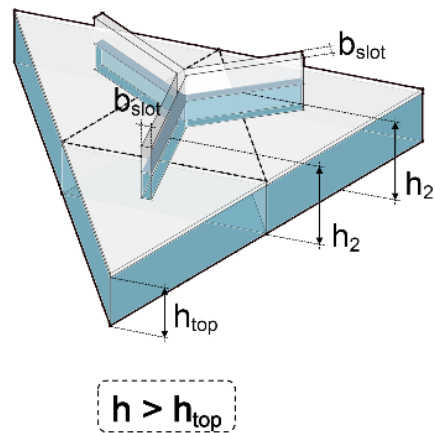
footprints and captures the transition from unpressurized to pressurized flow beneath piloti structures. Consequently, it allows for more accurate modeling of localized flood behavior, integrating piloti architecture into hydrodynamic models suitable for cultural heritage scenarios.

For each triangular mesh, three narrow slots are assumed at the top to connect adjacent mesh centers and extend infinitely upward (Fig. 4.3). Fig. 4.3a and Fig. 4.3b illustrate the slot arrangement for a central mesh and its three adjacent surrounding meshes. h_{top} denotes the height of the piloti, b_{slot} represents the uniform slot width in all three directions, and l_{slot} is defined as the sum of the lengths of three slots' centerlines inside one mesh. The total slot area for each mesh equals l_{slot} multiplied by b_{slot} , then minus the overlap area where three slots intersect at the mesh center. Dividing by the mesh area then yields the slot area ratio (r_{slot}). The model operates under two conditions: (i) when water depth h_1 is lower than h_{top} , free-surface flow occurs; (ii) when water depth h_2 is higher than h_{top} , pressurized flow occurs. During the pressurized period, the water exceeding h_{top} is compressed into the slot. Based on the principle of volume conservation, r_{slot} is used to calculate the equivalent average water depth for the entire mesh, which is then incorporated into shallow water equation computations. In accordance with Maranzoni (2015), the b_{slot} is set to 1% of the mesh characteristic length to achieve a balance between numerical stability and simulation accuracy.

a. Unpressurized Flow



b. Pressurized Flow



c. Slot Layout on Unstructured Grid

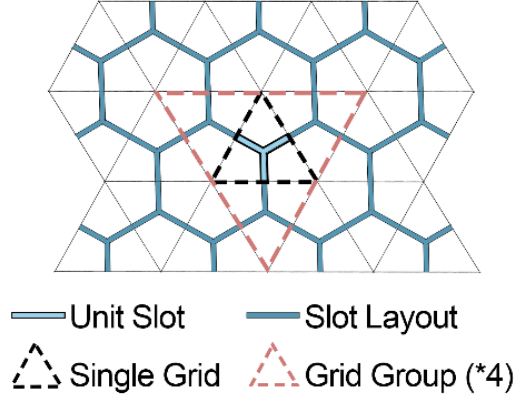


Figure 4.3 Slot configuration under (a) unpressurized condition and (b) pressurized condition;
 (c) Slot layout.

If h represents water depth in a mesh (including water in slot), H represents piezometric head, Z represents bed elevation, and h_{slot} represents actual mesh water depth accounting for water volume in the slot, then $H = h_{slot} + Z$. Water depth calculations for each inundation state follow: If $h \leq h_{top}$, $h_{slot} = h$; If $h > h_{top}$, $h_{slot} = h_{top} + (h - h_{top})/r_{slot}$.

4.2. Model validation: laboratory experiment

4.2.1. Experimental setup

Laboratory flume experiments were conducted to validate the accuracy of the slot-extended model established in Section 4.1. (Fig. 4.4). The architectural model was made as a rectangular block 0.45 meters long and 0.3 meters wide, representing a typical 9-meter-by-6-meter building unit in real cities, with a horizontal scale ratio $\lambda_{xy} = 20$. The height of piloti in the model is 0.06 meters, representing 0.6 meters in reality, with a vertical scale ratio $\lambda_z = 10$. The geometrically distorted scale model studies aim to ensure that it can represent real-world configurations (Dellinger et al., 2025; Li et al., 2024). Six ultrasonic sensors were positioned above the flume to detect water depth upstream, downstream, and laterally around the building model. Four of them were set up at the center of each side of the model (0.05 meters from the exterior walls). Two more sensors

were positioned far upstream and downstream, one meter away from the model. The purpose of the monitoring point layout is to focus on understanding the impact of the piloti structure on the flow of water in the main direction.

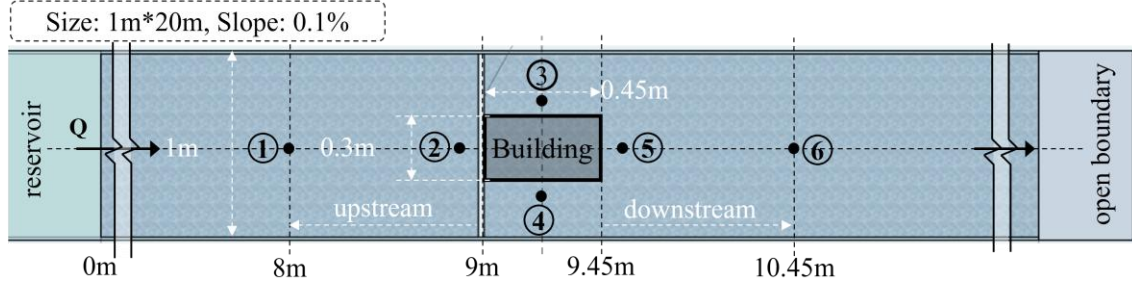


Figure 4.4 Experimental setup & observation points layout

Regarding the experimental setup, operations were conducted for both steady flow and unsteady flow conditions: (i) The main objective of the steady flow experiments was to validate the performance of the model under various steady states. Five different inflow discharges were selected, covering unpressurized flow, boundary flow, and pressurized flow scenarios (Fig. 4.5). Data were measured under steady conditions; (ii) the objective of the unsteady flow experiments was to validate the dynamic processes of the calibrated model. Three pressurized flow scenarios were conducted, with continuous data measurement throughout the entire process, from flow starts to steady states. Each experimental set was repeated three times, and the average value was taken to eliminate experimental error disturbance. The flow conditions for all experimental cases are shown in Table 4.1. The steady-state flow conditions achieved under the five experimental flow conditions are illustrated in Figure 4.6.

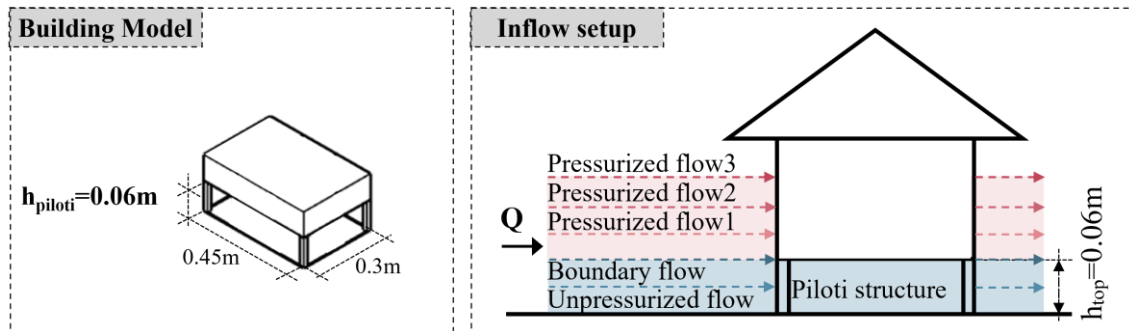


Figure 4.5 Inflow setup.

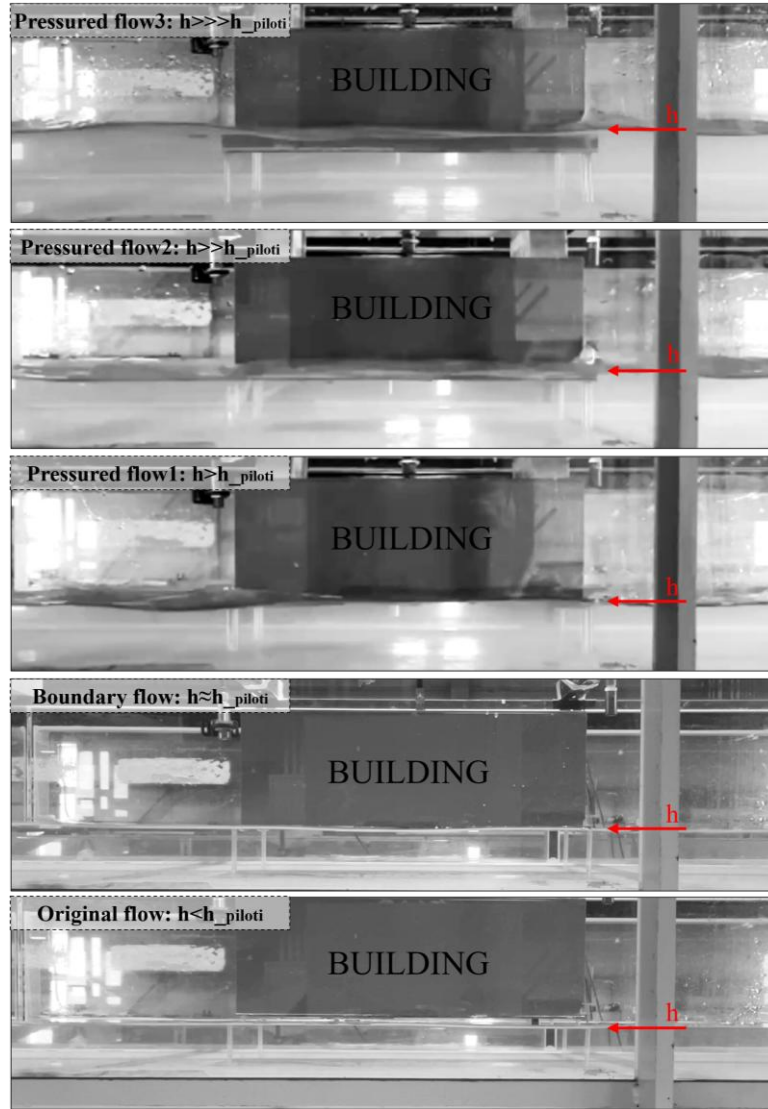


Figure 4.6 The experimental images under five inflow discharge.

Table 4.1 Flow conditions of experimental cases

Parameter	$f \mid Q$	h_{top}	h_{pre}	v_{pre}	Re	Fr
Unit	Hz $\mid$ m^3s^{-1}	m	m	ms^{-1}		
Steady flow	20Hz $\mid$ 0.00972	0.06	0.0422	0.2305	9681.2	0.3583
	30Hz $\mid$ 0.01903	0.06	0.0589	0.3231	18957.4	0.4251
	40Hz $\mid$ 0.02729	0.06	0.0711	0.3837	27177.7	0.4594
	50Hz $\mid$ 0.03495	0.06	0.0811	0.4312	34813.8	0.4836
	60Hz $\mid$ 0.04257	0.06	0.0901	0.4724	42400.1	0.5024

Subsequently, all experimental conditions were reproduced through numerical simulation. The unstructured mesh in the building area was designated as the piloti zone, with the same 0.06m elevation height. All other boundary conditions were maintained same as the model to validate the simulation accuracy of the slot-extended model.

4.2.2. Validation under steady conditions

Model validation under steady conditions seeks to show the model's precision in simulating water depth across diverse input scenarios. The experiments comprised five inflow discharges (9.72 L/s, 19.03 L/s, 27.29 L/s, 34.95 L/s, 42.57 L/s), leading to one unpressurized scenario, one boundary scenario, and three pressurized scenarios. Each scenario group has both experimental and simulated results. Figure 4.7 illustrates five scenario groups, each presenting experimental and simulated values for six observation points, as well as the relative error of the simulated values in relation to the experimental values. The majority of relative errors are contained under 5%. The slot-extended model accurately captures the water level rise at the front of the house (point 2) and the water level decline at the back (point 5), while the simulation error for the high water level at the front increases slightly with increasing inflow. The performance of the model at each observation point can be evaluated using Root Mean Square Error (RMSE) (Table 4.2). The average RMSE across all points is 0.002m, with an NSE of 0.986, demonstrating the simulation effectiveness of the 2D slot-extended SWEs under steady-state conditions with diverse inflow discharges.

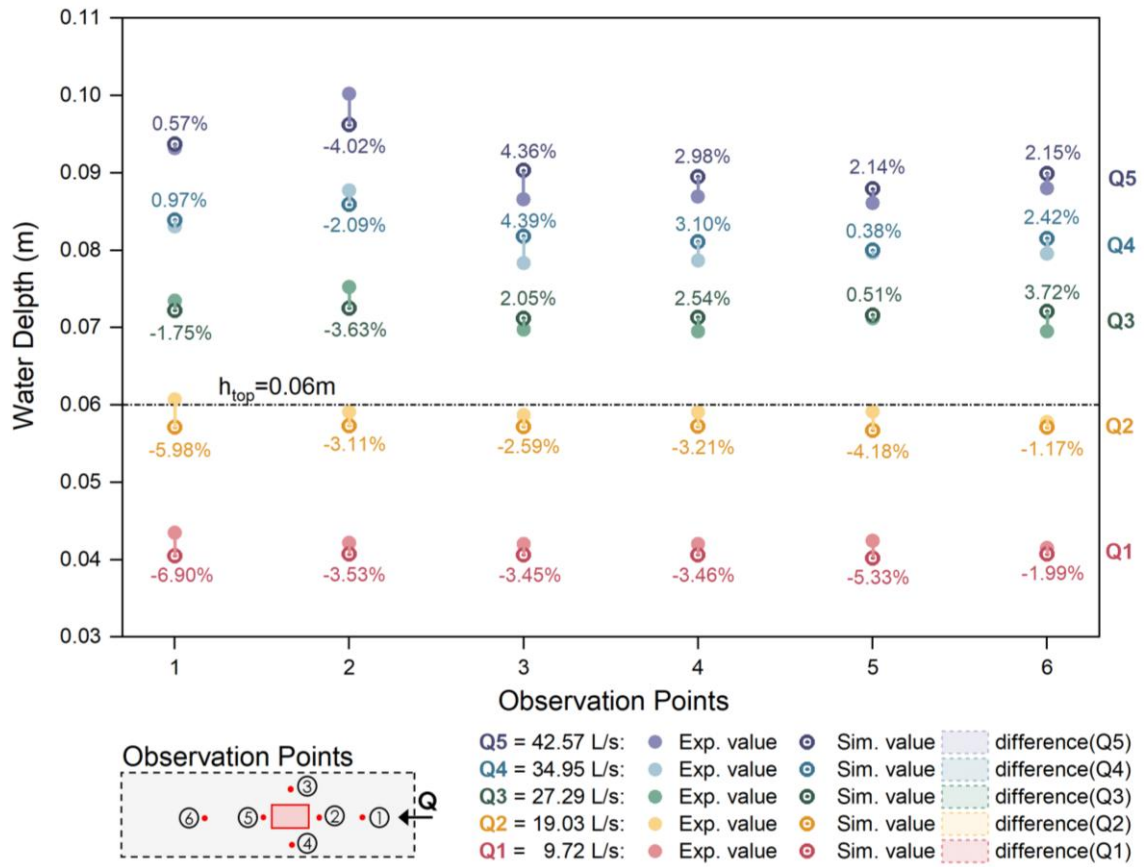


Figure 4.7 Simulation vs. experimental results under steady condition (with relative error).

Table 4.2 Results of the Validation under steady conditions.

Obs. Point	RMSE (m)
1	0.002
2	0.003
3	0.002
4	0.002
5	0.002
6	0.002
Average	0.002

4.2.3. Validation under unsteady conditions

Model validation under unsteady conditions seeks to verify the model's ability to accurately represent flood propagation dynamics across diverse inflow situations. The experiments involved three inflow discharges (27.29 L/s, 34.95 L/s, 42.57 L/s), creating various pressurized conditions. Figure 4.8 presents six subplots that contrast experimental and simulated results at six observation points, with each point's data encompassing three pressurized scenarios. The following phenomena were observed: (i) Across all six observed points, the transition from unpressurized to pressurized states (before and after reaching h_{top}) showed continuity in simulated values, despite a slight decrease in water depth acceleration near h_{top} ; (ii) In contrasting different observation points, the front-of-house location (point 2, Fig.4.8b) displays greater fluctuations in experimental values, which is accurately replicated by numerical simulations. Variations at other locations remain comparatively constant.

Owing to the disparity in time intervals between simulated outputs (10s) and experimental water depth measurements (0.2s), a time-scale matching is necessary for comparative analysis between simulated and experimental data. Experimental data are centered and averaged through resampling to align with simulated output time points. For each 10-second interval, the experimental values from the previous and next 5-second periods are averaged to get the experimental water depth corresponding to the simulated result timepoint. The performance of the model is subsequently assessed using this modified data. The results (Table 4.3) indicate that the average RMSE varies from 0.003m to 0.005m across all points and inflow scenarios, and the NSE ranges from 0.884 to 0.953. This indicates that the slot-extended model accurately represents flood propagation dynamics across diverse unsteady inflow conditions.

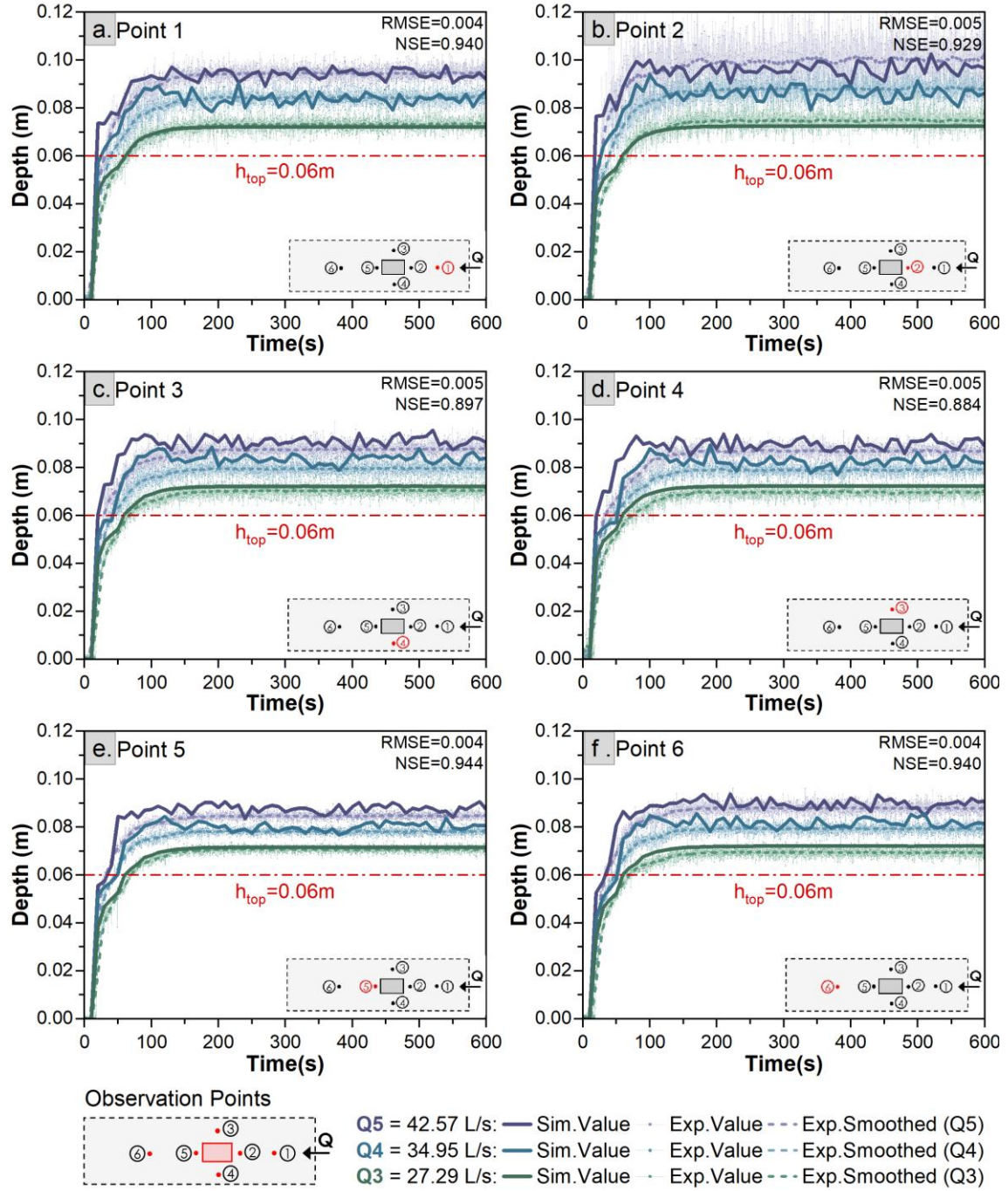


Figure 4.8 Simulation vs. experimental results under unsteady conditions.

Table 4.3 Results of the Validation under unsteady conditions (point1-4).

Inflow	1		2		3		4	
(L/S)	RMSE (m)	NSE	RMSE (m)	NSE	RMSE (m)	NSE	RMSE (m)	NSE
27.29	0.002	0.973	0.003	0.958	0.003	0.953	0.004	0.924
34.95	0.005	0.918	0.005	0.929	0.006	0.860	0.006	0.869
42.57	0.005	0.930	0.006	0.899	0.006	0.877	0.006	0.859
Ave.	0.004	0.940	0.005	0.929	0.005	0.897	0.005	0.884

Inflow	5		6		Ave. Value	
(L/S)	RMSE (m)	NSE	RMSE (m)	NSE	RMSE (m)	NSE
27.29	0.002	0.971	0.004	0.941	0.003	0.953
34.95	0.004	0.942	0.004	0.931	0.005	0.908
42.57	0.005	0.920	0.004	0.948	0.005	0.906
Ave.	0.004	0.944	0.004	0.940	0.004	0.922

4.3. Model application: the impacts of piloti in heritage sites

4.3.1. Spatial arrangement and parameter settings of piloti

Section 3 has detailed the input data categories and preprocessing for the numerical model. The application of this slot-extended model was conducted at Shimogamo Shrine and Katsura Imperial Villa. For the 1.1 km² study area at Shimogamo Shrine, GiD software generated 49,177 unstructured meshes with element sizes ranging from 1 to 8 meters. Beyond the standard piloti structure with an elevated ground floor, Shimogamo Shrine features a distinct form we term “elevated structure.” These structures raise the ground floor while enclosing the external walls of the elevated space, preventing water flow and forcing it to bypass. However, the actual indoor floor level remains elevated. Therefore, we uniformly treated these structures in the simulation as localized

topographical elevations to replicate their observed effects (Fig. 4.9). For the Katsura Imperial Villa study area, GiD software generated 61,987 unstructured meshes across a 1.77-square-kilometer simulation zone, with mesh edge lengths ranging from 1 to 8 meters. All six main buildings surrounding the lake feature piloti structures, though at varying heights. In the simulation, each building's piloti height parameter was assigned individually (Fig. 4.10). Subsequently, the validated slot-extended model was applied to conduct inundation simulations for separate heritage sites.

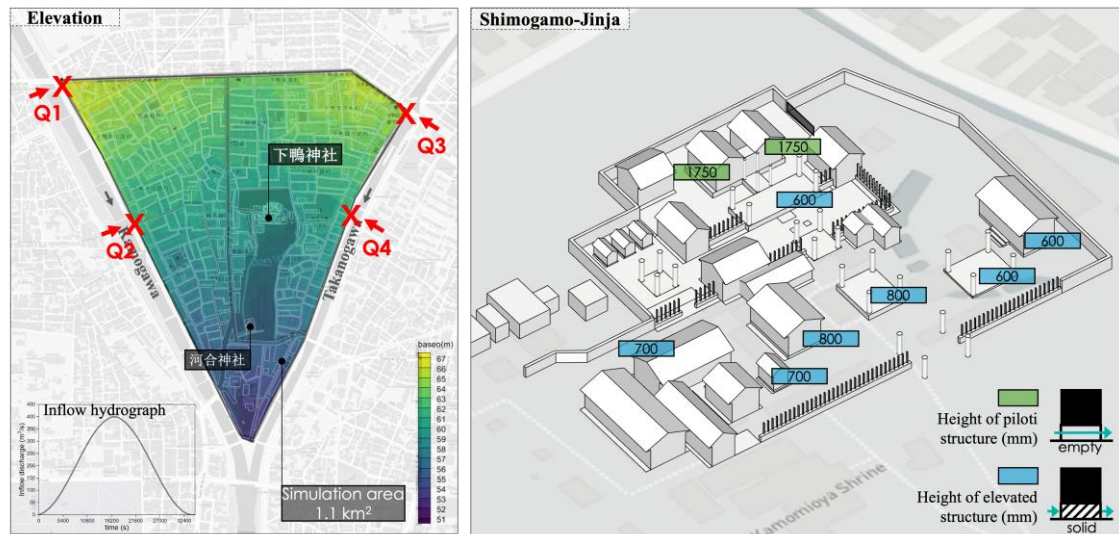


Figure 4.9 Spatial arrangement and parameter settings in Shimogamo-Jinja

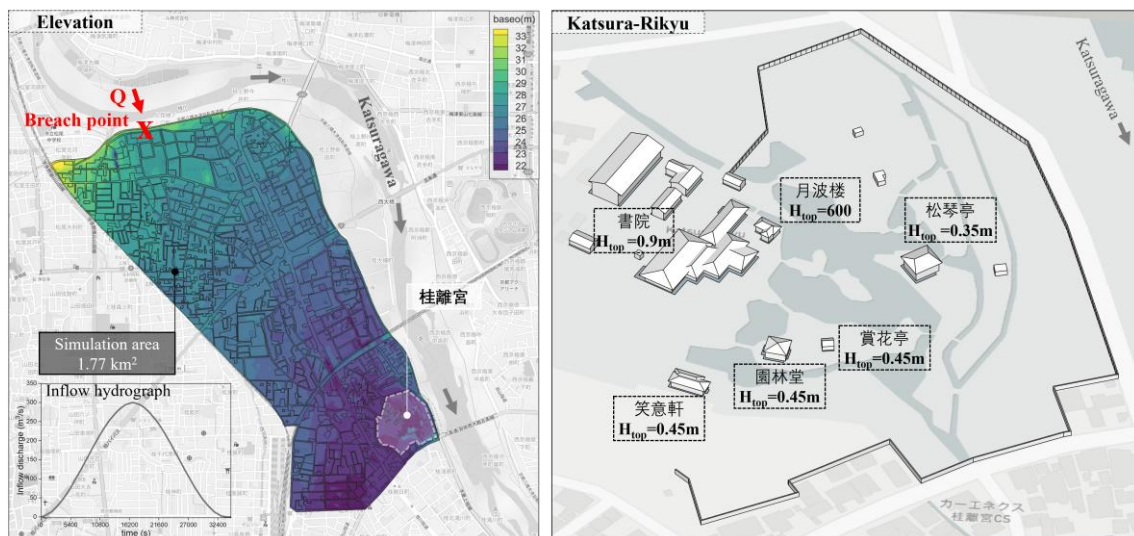


Figure 4.10 Spatial arrangement and parameter settings in Katsura-Rikyu

4.3.2. Necessity of representing piloti in flood modeling

Simulations were conducted for two study areas, each examining two scenarios: the actual with piloti scenario (Scenario A) and a virtual comparison without piloti (Scenario B). Scenario A applied the slot-extended model to the simulation area to account for the presence of elevated structures at ground level. Scenario B disregarded the characteristics of the building's lower levels, assuming all structures were built directly on the ground.

Figure 4.11 presents simulation results for the entire simulation area encompassing Shimogamo Shrine and its surrounding area, comparing the spatial distribution of maximum water depth under two scenarios: with and without piloti structures. Since the single simulation variable (piloti) exists only within a very small portion of the site, the overall difference is indistinguishable. The distribution shows that water depth increases in areas where the terrain slopes downward. Located at the center of the simulation area, the main structure of Shimogamo Shrine on the northern side experiences moderate flood depths. In contrast, Kawai Shrine on the southern side suffers significantly greater flood depths. Focusing specifically on the core building complex of Shimogamo Shrine reveals distinct spatial differences between the two simulation scenarios. Figure 4.12 presents an enlarged comparative view. Water depths within the building zones are noticeably lower in Scenario A when considering the piloti structure, while the surrounding areas immediately adjacent to the buildings exhibit slightly deeper water levels than in Scenario B (which disregards the piloti structure). These results demonstrate the redistributive effect of the piloti on floodwater distribution across the site.

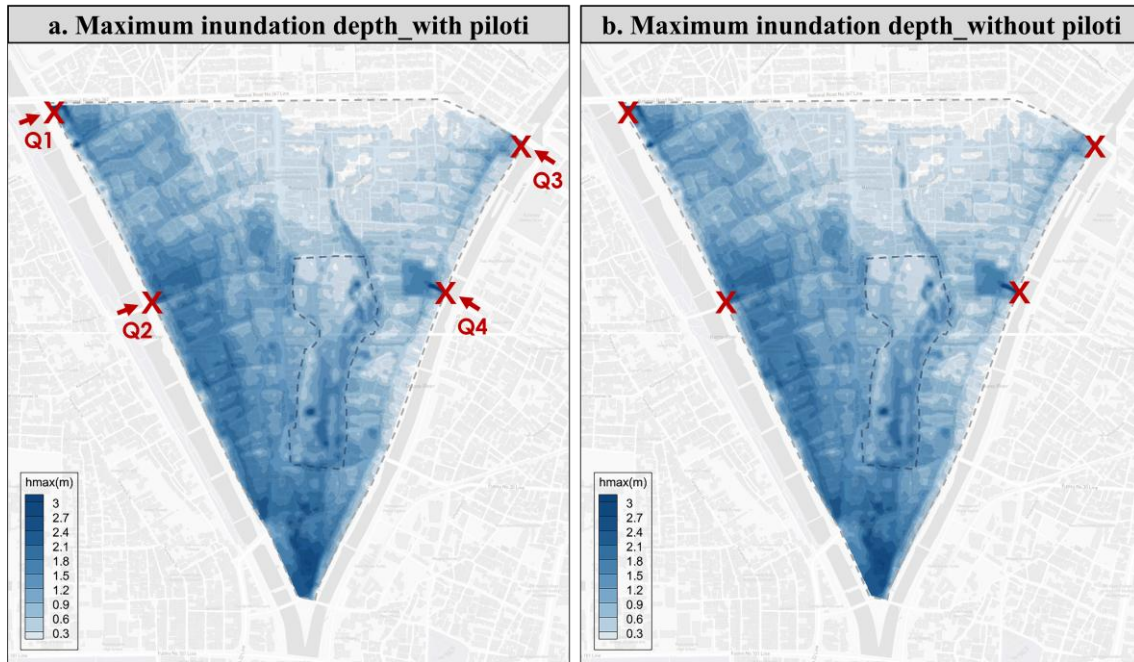


Figure 4.11 Maximum water depth of Shimogamo-Jinja and its surroundings

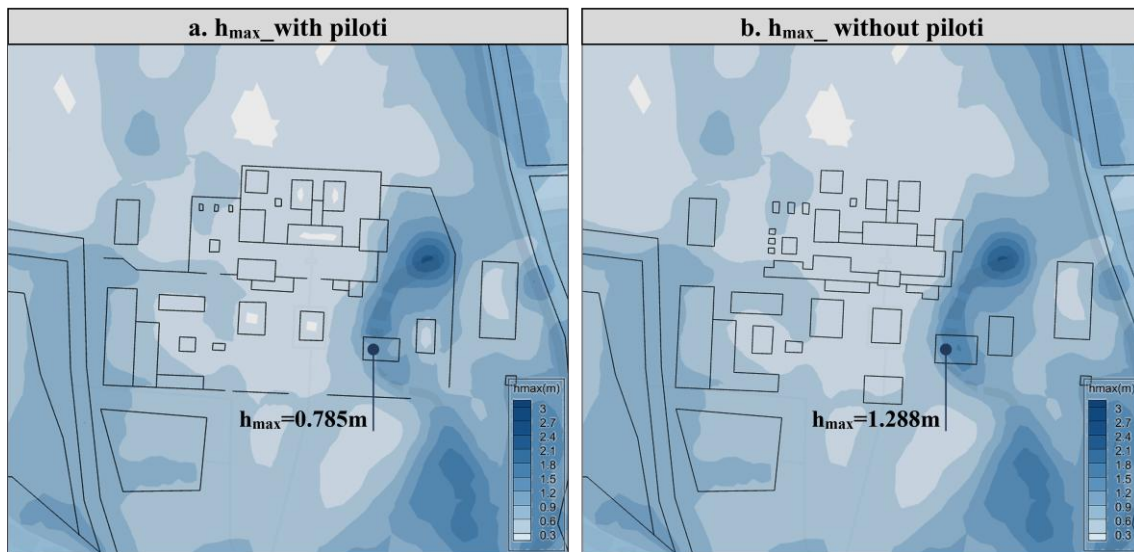


Figure 4.12 Maximum water depth of the center heritage area at Shimogamo-Jinja

The simulation results for Katsura Imperial Villa and its surrounding areas show a high degree of similarity to those of Shimogamo Shrine, with even clearer outcomes. Overall simulation results remain largely consistent across both scenarios (Fig. 4.13), as the piloti structures at Katsura Imperial Villa are also concentrated in localized areas. Due to its closer proximity to the riverbank and relatively lower elevation, Katsura Imperial Villa experienced the deepest water levels. Focusing specifically on the core building

complex within Katsura Imperial Villa featuring piloti (Fig. 4.14), a distinct boundary line separates the water depth within the building area from that of the surrounding region. This water depth boundary closely aligns with the height of the building footprint, further highlighting the direct influence of the piloti structure on the simulation results.

Simulation results for both sites indicate that at the basin or urban scale, considering building ground-floor structures has limited impact on large-scale water depth patterns and maximum inundation areas. However, when analyzing localized flood behavior at sites like cultural heritage areas, ground-floor structures significantly alter inundation dynamics within courtyards. Overlooking such details in modeling can lead to significant errors in predicting individual building inundation levels. This underscores the necessity of accurately representing ground-floor spatial configurations in models for cultural heritage sites, making the 2D slot-extended model an essential component of refined modeling for heritage preservation.

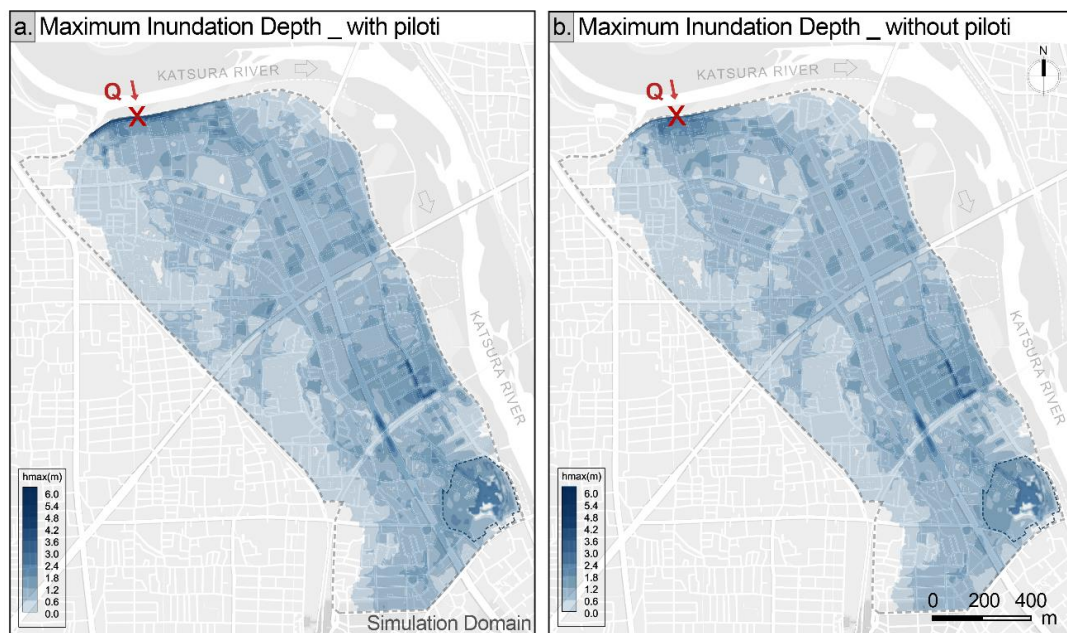


Figure 4.13 Maximum water depth of Katsura-Rikyu and its surroundings

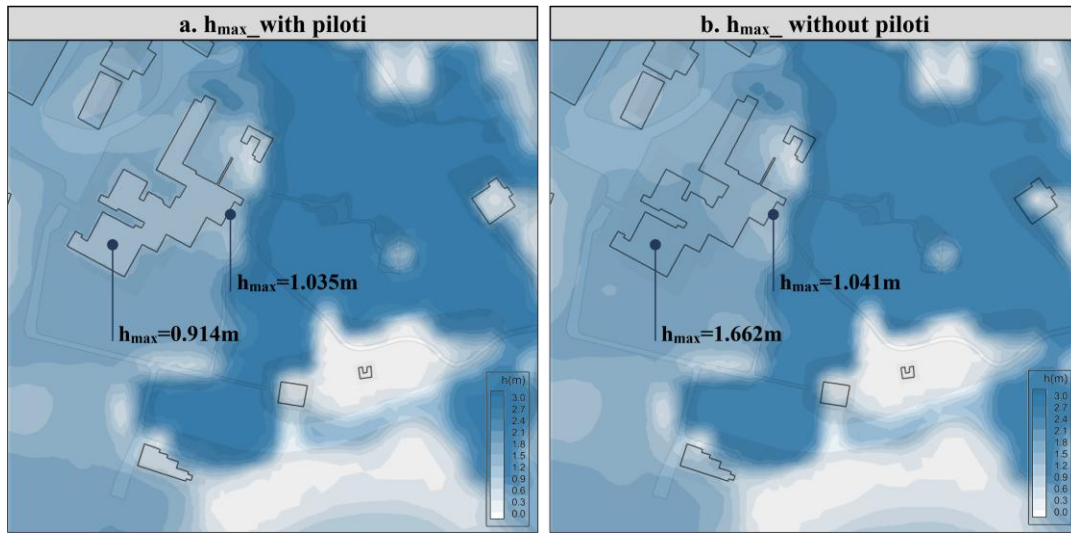


Figure 4.14 Maximum water depth of the center heritage area at Katsura-Rikyu

4.3.3. Hydrodynamic mechanism of flow through piloti

Given that the piloti structure is more representative in the Katsura Imperial Villa case, this section will further analyze the flood prevention mechanism of piloti using this villa as an example. According to the simulation results for maximum water depth (Fig. 4.14), the presence of piloti significantly reduces the maximum water depth in the building area, while the surrounding areas show little overall change. Combined with the spatial variation of maximum flow velocity (Fig. 4.15), it is evident that velocity changes gradually across most areas, with generally low velocity values. However, when considering piloti, velocity peaks and wake trails descending along the slope appear at building corners very close to the lake. This phenomenon is absent in the scenario without piloti. Further analysis of the peak flow field patterns shown in Figure 4.16 reveals that, particularly near buildings with higher flow velocities and trailing effects, floodwater transitions from primarily bypassing the structure to directly traversing the building's ground floor.

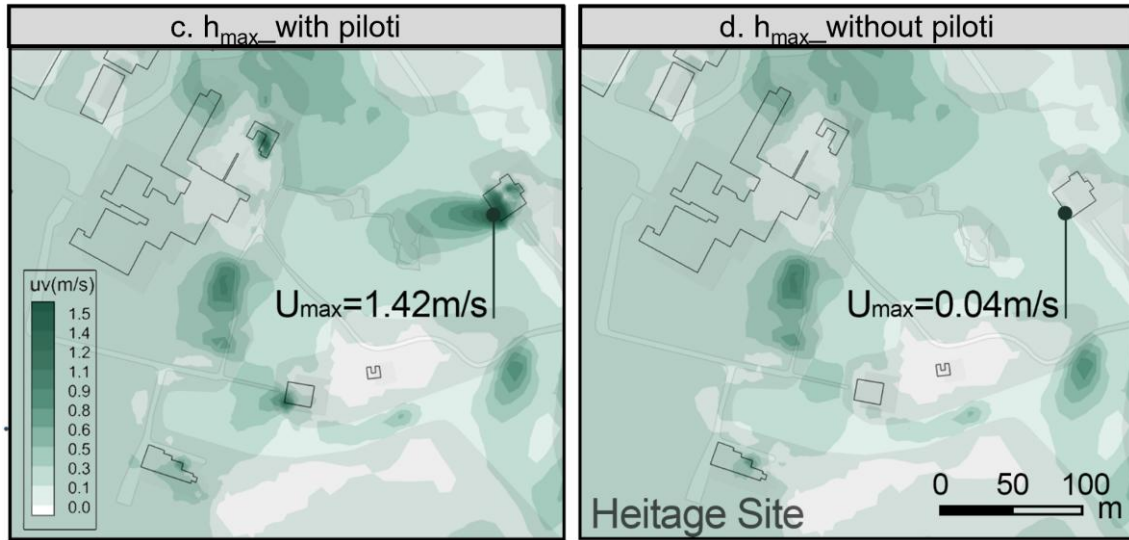


Figure 4.15 Maximum flow velocity of the center heritage area

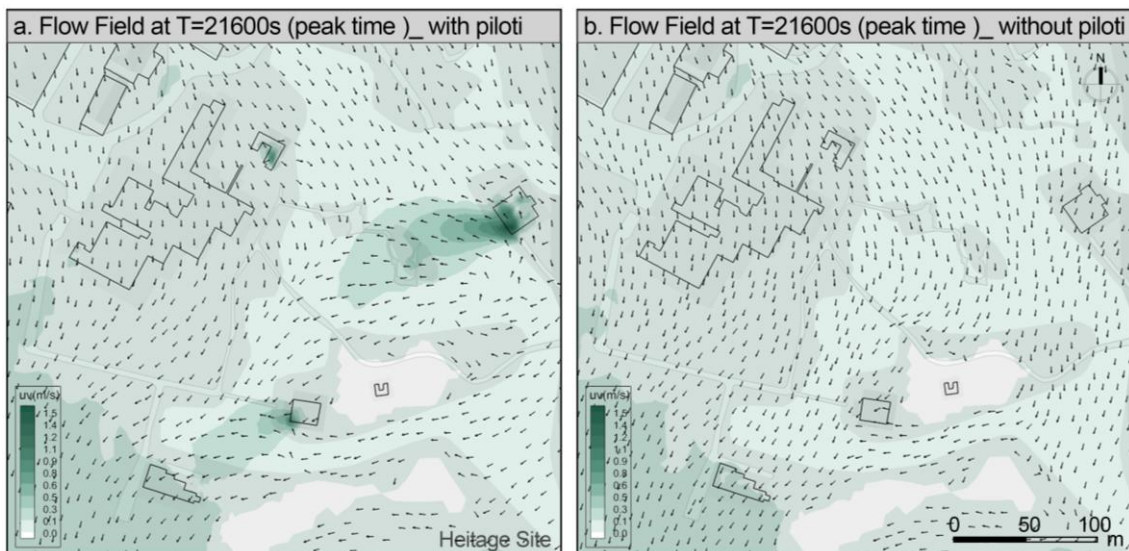


Figure 4.16 Flow field of the center heritage area

These phenomena are presumed to reflect the potential flood mitigation mechanism of piloti. They create new pathways for floodwaters to pass directly beneath the building while elevating the functional floor level. Under identical inflow conditions, the water level on the upstream side is reduced, the inflow rate into the building area slows, and the water depth becomes less. In contrast, without piloti, incoming flow must either flow around or over the structure, making the upstream side more likely to accumulate water and resulting in higher steady-state water volumes within the building. Meanwhile, the presence of piloti also shows a slight increase in flow velocity across the site. This is

hypothesized to occur because the introduction of the ground-level channel redistributes the local flow field, accelerating the flow beneath the structure during the early simulation stages. The examination of 12 representative exterior points around the main buildings of Katsura Imperial Villa suggests that piloti reduces water depth around the exterior wall. While flow velocity data indicate a slight increase, the overall flow is characterized by low velocities. The effect of isolated high-velocity points (such as Point 8) needs further individual consideration (Fig.4.17).

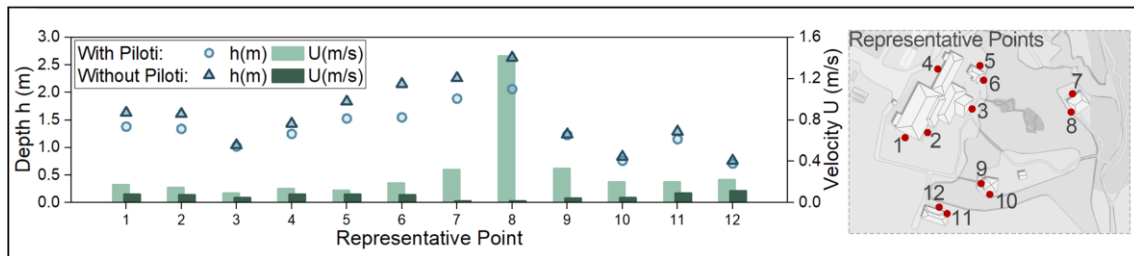


Figure 4.17 Comparison of water depth and velocity at 12 representative points.

The occurrence of isolated high-velocity points is reasonable, likely occurring at the corners of individual buildings. Due to the significant elevation drop near the lake surface, water flow experiences localized acceleration after passing through the piloti structures, influenced by the hydraulic head difference. However, the potential structural damage risks posed by these localized high-velocity flows require independent consideration. The accepted approach involves jointly assessing their hazard level based on both water depth and flow velocity. Simulation results reveal that point 8 (Fig. 4.17) witnesses the maximum flow velocity ($U = 1.42 \text{ m/s}$; $h = 2.06 \text{ m}$). The stability evaluation criteria of wooden building established by MLIT (2017) (Fig. 4.18) and Natural Resources Canada (2021) (Fig. 4.19) both suggest that there will be no collapse or sliding under these conditions. Therefore, building-level failure (overturning or sliding) is not expected at this location. Nevertheless, these criteria target timber structures in normal conditions. For heritage buildings, maintenance state and aging may alter their stability and thus affect the assessment. To keep the scope clear, we assume the key buildings are well maintained and structurally in good condition.

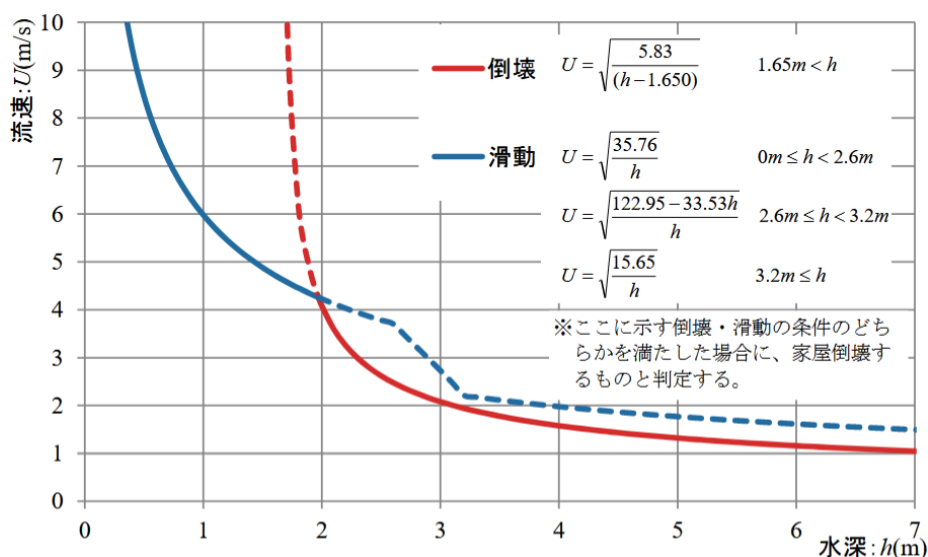


Figure 4.18 The collapse limit for wooden houses in Japan (source: 洪水浸水想定区域図作成マニュアル(第4版))

Material	No. Storeys	Depth Threshold (DT) (m)	Velocity Threshold (VT) (m/s)	Collapse Potential			
				V < 0.6 m/s at any Depth	V < VT and D < DT	V < VT and D ≥ DT	V ≥ VT at any Depth
Wood	1 Storey	3.05	1.63	No collapse	No collapse	Collapse	Collapse if D > 268.38 V(-1.9642)
Wood	2 Storey	4.57	1.32	No collapse	No collapse	Collapse	Collapse if D > 268.38 V(-1.9642)
Wood	3 Storey	6.10	1.14	No collapse	No collapse	Collapse	Collapse if D > 268.38 V(-1.9642)
Wood	4+ Storeys			No collapse	No collapse	No collapse	No collapse

Figure 4.19 The collapse limit for wooden houses in Canada (source: Federal Flood Damage Estimation Guidelines for Buildings and Infrastructure (version 1.0))

It should be noted that when the flow is partially constrained by piloti, the ground floor space will experience locally pressurized conditions. This can modify the pressure distribution around the building and increase buoyancy force on structures. Meanwhile, as the head difference evolves during the flood process, lateral water pressure and localized hydrodynamic actions may also be increased. Therefore, beyond hydrodynamic indicators, further work on global structural stability is essential. Specifically, translating simulated water depth and velocity fields into flood induced external loads for stability assessment.

4.4. Summary

The work summarized in this chapter is as follows:

- 1) The slot-extended model can accurately reproduce mixed flow under piloti.

Building upon the traditional shallow water equations, this chapter achieves dynamic simulation of continuously varying mixed flow states by introducing a virtual “slot” at the top of the 2D unstructured mesh. Systematic validation through flume tests demonstrates that the slot-extended 2D hydrodynamic model accurately reproduces water depth variations at key cross-sections upstream and downstream of piloti under both steady and unsteady conditions. Average RMSE and NSE values reach 0.002m and 0.986 (steady condition) and 0.004m and 0.922 (unsteady condition), validating its reliability for handling 2D mixed flows. It should be noted that water depth errors near the building's upstream face exhibit a slight increase under high-flow conditions (Fig. 4.7, point 2). A reasonable hypothesis is that the model slightly underestimates resistance within the elevated ground floor channel, such as by neglecting friction forces on the ceiling slab. Future work will incorporate new friction or resistance terms to further enhance model accuracy. Overall, this model successfully links the architectural feature of piloti with the hydraulic response of pressurized flow, providing a crucial numerical supplement for subsequent detailed building-scale inundation simulations in heritage contexts.

- 2) It is essential to account for piloti structures in heritage-scale 2D simulations.

Numerical comparisons indicate that while considering ground-floor structures have limited impact on overall flooding at larger regional scales, piloti significantly alter water depth and flow patterns within courtyards at the local scale of cultural heritage sites. Completely ignoring these specialized ground-level structures in modeling may underestimate or overestimate the inundation levels and localized hydrodynamic effects on critical buildings, thereby affecting quantitative predictions of flood severity across different spatial scales. This chapter's analysis demonstrates that incorporating piloti spatial characteristics into 2D hydrodynamic modeling is a necessary foundation for detailed assessments aimed at cultural heritage preservation.

- 3) The dual impact of piloti structures on heritage buildings.

From the perspective of local hydrodynamic processes, piloti open new flow

pathways beneath buildings. The incoming flow transitions from a free surface to pressurized flow within the elevated layer, creating relatively concentrated flow channels in the ground-level space. On one hand, the elevated ground floor significantly reduces peak water depth and inundation duration in functional floors (raised levels). From the perspective of hydraulic pressure and buoyancy risks, this helps mitigate damage, saturation, and mold risks within the building structure, providing direct protection to the heritage structure itself. On the other hand, the overall flow velocity in the heritage area slightly increases, with localized high-velocity zones appearing (particularly at void exits and building corners). This indicates heightened erosion and shear risks in these areas, necessitating specialized damage assessment and targeted protective measures in conjunction with material and structural durability considerations.

5. Hydraulic Experiments and Modeling of Porous Fence

Fences represent the most fundamental method of spatial division, widely employed in garden design to define distinct areas or separate interior and exterior spaces. Fences are typically categorized into solid fences, porous fences, and composite fences. They serve as essential spatial elements within Kyoto's cultural heritage sites, though specific materials and porosity vary slightly based on requirements. For instance, the outer enclosure wall at Shimogamo Shrine primarily consists of solid walls, creating a complete barrier between interior and exterior spaces. The inner enclosure wall predominantly features a composite structure, solid at the base with highly porous fences above, limiting space while maintaining visual connectivity. Katsura Imperial Villa presents a unique case. Its eastern wall facing the Katsura River features a base of densely arranged low-porous bamboo fence. Over this, living bamboo from the inner grove is bent and woven to form the Katsuragaki (桂垣). As the bamboo continues to grow, the porosity of this section gradually decreases. The northern section of Katsura Imperial Villa, known as Hogaki (穂垣), shares a similar configuration to Katsuragaki but lacks the covering of living bamboo. Field research indicates that despite their visual differences, the outer-facing surfaces of both structures are essentially mirror images of each other, sharing identical configurations (Fig. 5.1). Consequently, they can be treated identically in subsequent numerical simulations. From a landscape design perspective, such bamboo walls integrate more harmoniously with nature, maintaining visual and experiential coherence with the surroundings while also serving as spatial dividers. Growing alongside the site's vegetation, these walls acquire deeper significance as living entities.



Figure 5.1 The bamboo fences in Katsura-Rikyu

Beyond its landscape value, this study focuses more on the flood mitigation function

of the porous fence, a crucial element within the heritage space. While the solid fence undoubtedly blocks floodwater to a certain extent, as a hard measure, it becomes ineffective once floodwater exceeds the wall's height or the wall itself is breached, allowing the flood to attack the enclosed space with even greater force. In contrast, porous fences represent a soft measure. While they cannot completely block floodwaters, they enable the coexistence of heritage sites and floods by slowing flood progression and reducing peak flow. Existing studies on flood management at Katsura Imperial Villa consistently recognize Katsuragaki as a vital passive flood control strategy, capable of filtering debris from incoming floodwaters and mitigating flood intensity (Kawasaki et al., 2013; Okubo, 2016). However, existing studies lack a clear definition of the hydrodynamic response of porous fences during floods, as well as scientific understanding and reasonable modeling methods for the drag force generated by fences with different porosities from a hydraulic perspective. Based on this understanding, this chapter focuses on idealized porous fences. Through systematic flume experiments and drag coefficient fitting, a drag expression suitable for 2D SWEs would be developed. Furthermore, the hydrodynamic impacts of porous fences in typical cultural heritage sites are analyzed.

Existing research in related fields has not directly addressed the hydrodynamic modeling of porous fence in urban flooding, but several closed studies provide valuable references for this investigation. Studies on gabion weirs have established empirical flow coefficient formulas using dimensionless parameters such as Froude number and relative water depth. These formulas were derived from systematic flume tests measuring water level and flow variations upstream and downstream under varying porosity, weir height, and inflow conditions. Although the research objectives differ, the experimental design approach and parameter selection methods in these studies offer valuable insights for the present work (Salehi and Azimi, 2024; Shariq et al., 2022, 2020). Furthermore, multiple studies on the drag coefficients of obstacles such as buildings and column fields have measured external forces, water depth, and flow velocity, then calculated the drag coefficient C_d using drag formulas. These findings also provide reference pathways for calibrating and modeling the drag coefficient of porous walls in terms of the definition

approach and computational framework. (Fukuoka et al., 1997; Suenaga et al., 2014; Takahashi et al., 1985).

This paper develops a flood model applicable to heritage structures featuring porous fences, a characteristic architectural feature, by addressing the unique properties of such structures. First, hydraulic performance tests in a flume laboratory were conducted to determine the hydraulic response of porous walls with various porosity levels under different inflow discharge and wall thicknesses. Then, through resistance coefficient calculations and univariate analysis, an empirical equation for C_d was ultimately fitted. The drag coefficient is then incorporated into the 2D SWEs and validated against experimental data. Finally, applying the improved model that accounts for porous fences to flood simulations at Shimogamo Shrine and Katsura Imperial Villa demonstrates the necessity of the expanded model compared to the original simulation that disregards porous fences, and explains the flood prevention mechanism of porous fences. Figure 5.2 illustrates the three main steps of this chapter's research:

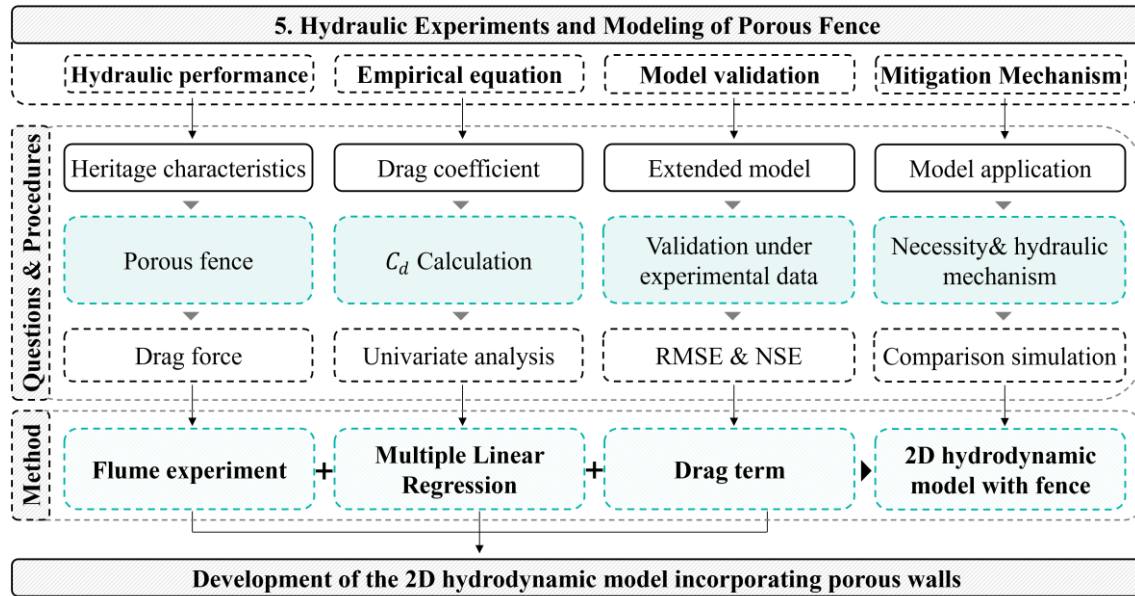


Figure 5.2 Research framework of Chapter 5

5.1. Hydraulic experiment of porous fence

5.1.1. Typical physical characteristics

The presence of a fence directly restricts water flow. A solid fence completely blocks water flow, causing the water body to bypass the structure, while a porous fence allows a portion of the water flow to pass through (Fig. 5.3). It is reasonable to assume that the smaller the porosity, the closer the restriction effect approaches that of a solid fence. Therefore, it is not difficult to predict that the presence of fences with different porosities directly influences flood behavior. However, in real-world environments, it is difficult to observe the hydrodynamic performance of fences with varying porosities during floods. Therefore, flume experiments are set up to deeply understand the specific phenomena and translate their effects into parameters within a 2D hydraulic model. To maximize the applicability of research findings, this study selected fence porosity, wall thickness, and inflow discharge as primary variables to derive empirical equations for the drag coefficient, matching uncertain hedge porosity and varying natural fences. The experimental procedure comprised three steps: (i) preliminary experiments to establish baseline hydraulic conditions in the flume; (ii) steady-state flow experiments for phenomenon analysis, variable correlation studies, and C_d value calculations; (iii) unsteady-state flow experiments for mechanism analysis and model validation.

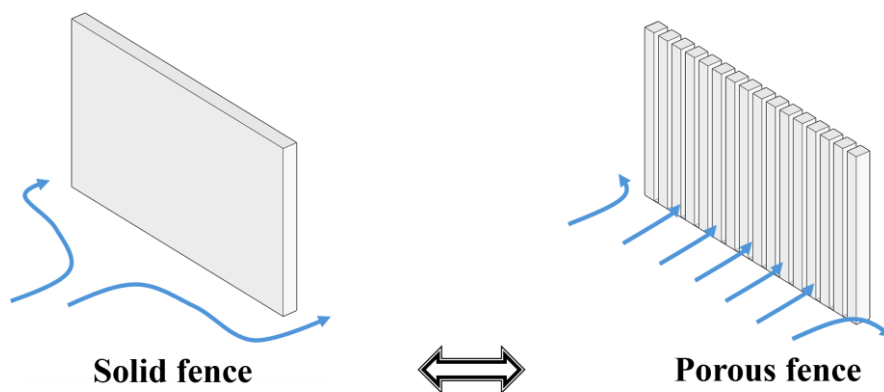


Figure 5.3 Diagram of different fences

5.1.2. Experimental setup

This chapter primarily investigates the hydrodynamic response of porous fences using laboratory experimental methods. To extract the average resistance coefficient of porous walls during flood flow, this study treats them as a single obstacle without considering detailed flow conditions within the gaps. At the initial stage of experimental design, a dimensional analysis was first conducted. The fundamental physical quantities selected for the study include porosity γ , inflow discharge Q , wall thickness d , initial water depth h_0 , fluid density ρ , dynamic viscosity μ , and gravitational acceleration g . These quantities encompass three fundamental dimensions: M, L, T . Applying Buckingham's Π theorem allows the construction of several dimensionless parameters. Using the drag coefficient C_d as the dependent variable and the γ , the ratio of d to h_0 is used as the independent variable, yielding the general form:

$$C_d = f\left(\gamma, Fr, Re, \frac{d}{h_0}\right)$$

Here, $Fr = v/\sqrt{gh_0}$ reflects the ratio of inertial forces to gravitational forces, while $Re = \rho vd/\mu$ represents viscous effects. Since all operating conditions fall within the fully turbulent regime, the Fr similarity principle was prioritized in this experiment. The results of the dimensional analysis provide a theoretical basis for subsequent operating condition combinations and the selection of empirical formulae for C_d .

Based on the dimensional analysis, this study designed channel experiments focusing on three key factors: porosity γ , inflow discharge Q , and wall thickness d . Experiments were conducted on a rectangular channel with a porous wall positioned at the channel's central section (Fig. 5.4). A total of six ultrasonic sensors were positioned within the flume: two sensors were placed equally upstream of the wall, while four sensors were arranged downstream from the near to far positions. This configuration enabled comprehensive capture of water level variations both upstream and downstream of the porous wall. The geometric scale was selected as $\lambda_L = 15$.

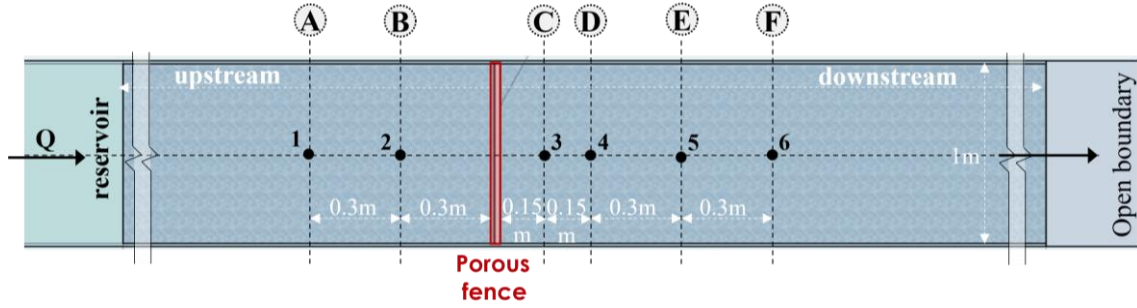


Figure 5.4 Experimental setup & observation points layout

The porous fences commonly found in cultural heritage sites typically share a similar construction: primarily composed of vertical poles with horizontal frames for stabilization. The porous fence model in this experiment was similarly constructed (Fig. 5.5). fences with varying porosity γ (seven levels from 0.1 to 0.5) were achieved by altering the spacing between vertical wooden rods ($Porosity(\gamma) = S_{gap}/S_{total}$). Additionally, rod thickness was adjusted to simulate different wall thicknesses d (five levels from 2 mm to 6 mm). The experiment also tested models constructed with wooden rods of two different materials to observe whether material type influenced the experimental results.

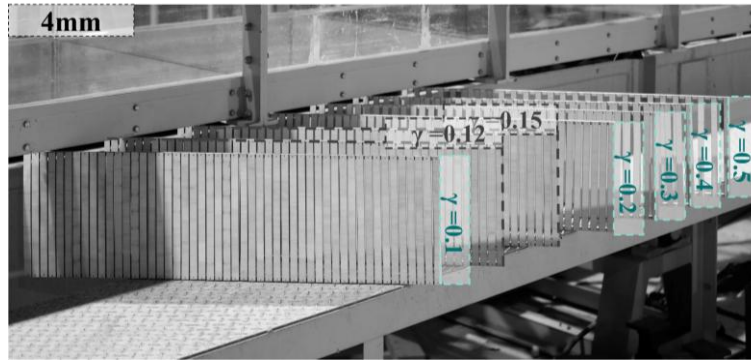


Figure 5.5 Porous fence model construction (4 mm cases)

5.1.3. Experimental results and hydraulic performance

1) The flow conditions of each experimental case

The experiments ultimately established combining operating conditions for different variables (γ, Q, d) to systematically investigate the influence of each parameter on the drag coefficient C_d of porous walls. A total of 63 experiments were conducted under steady conditions, and 35 under unsteady conditions, with each operating condition tested in three separate rounds. Typical experimental phenomena are illustrated in Figure 5.6.

The specific parameters for each condition are listed in Table 5.1.

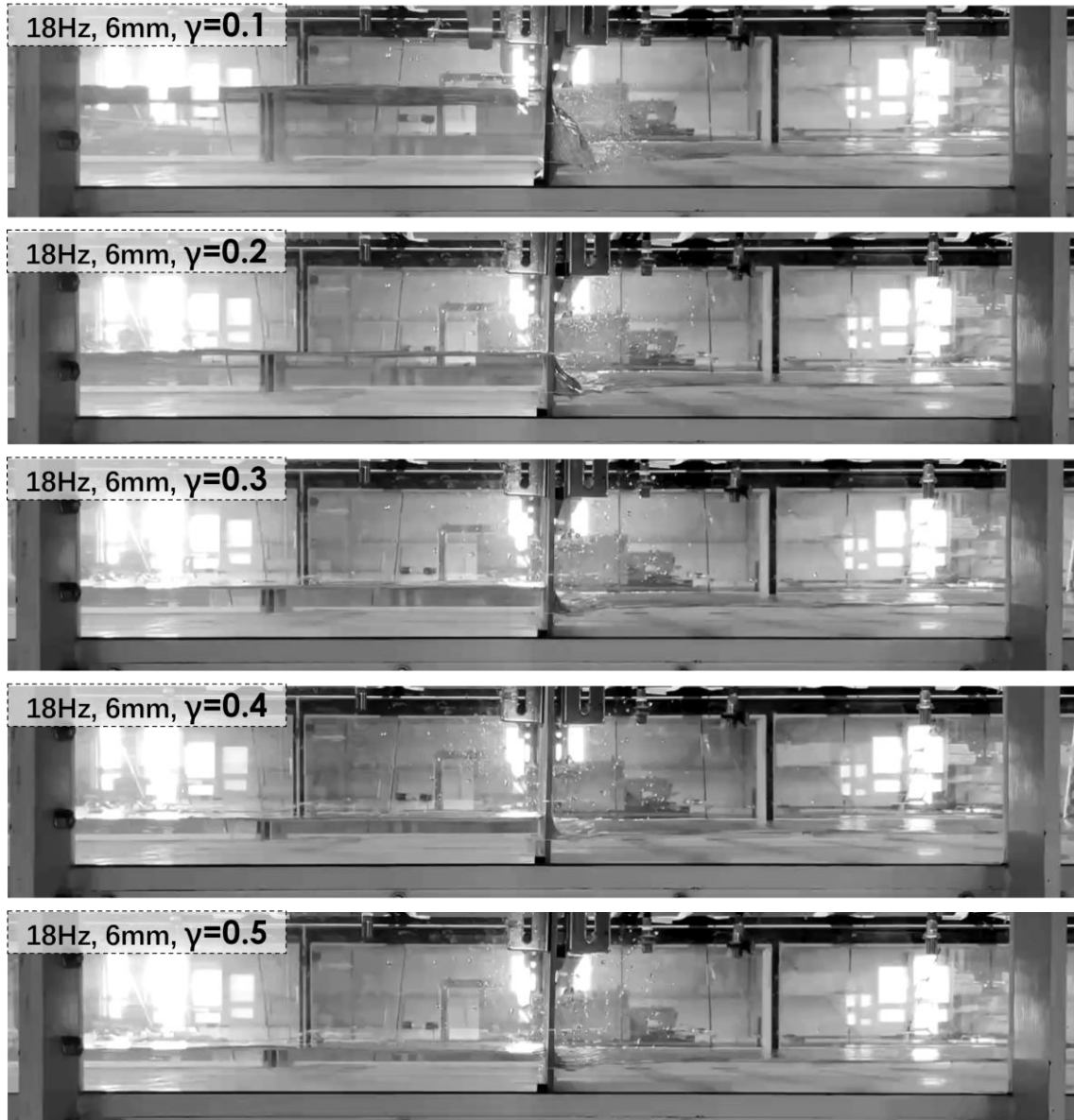


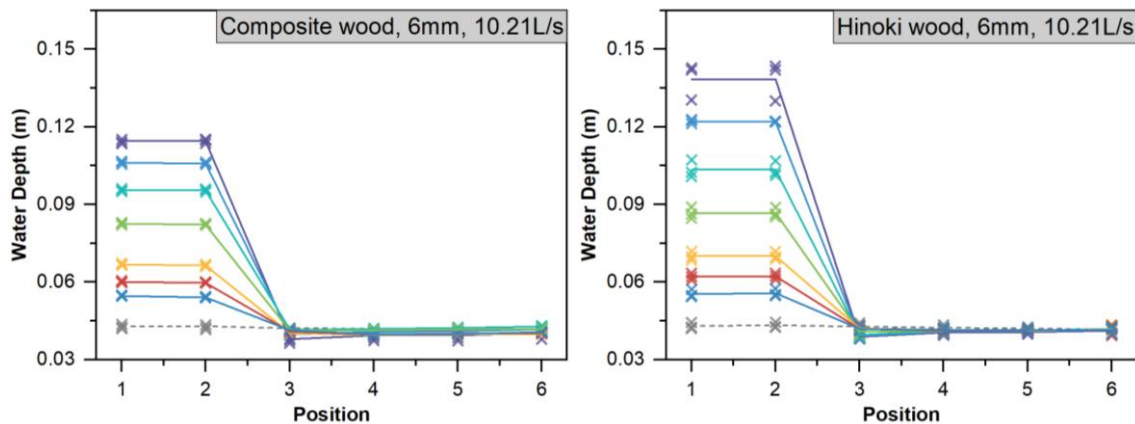
Figure 5.6 The experimental images under five porosities.

Table 5.1 Flow conditions of experimental cases (gray-shaded cases also include unsteady condition experiments)

d	f	Q	γ	h_0	v_0	Re	Fr
m	Hz	m^3s^{-1}		m	ms^{-1}		
2mm	18Hz 0.00621		0.1/0.12/0.15/0.2/0.3/0.4/0.5	0.0334	0.1858	6185	0.3237
	21Hz 0.00983		0.1/0.12/0.15/0.2/0.3/0.4/0.5	0.0421	0.2337	9791	0.3637
	24Hz 0.01291		0.1	0.0475	0.2717	12858	0.3979
3mm	18Hz 0.00673		0.1	0.0347	0.1942	6703	0.3330
	21Hz 0.01044		0.1	0.0430	0.2426	10398	0.3733
	24Hz 0.01336		0.1/0.12/0.15/0.2/0.3/0.4/0.5	0.0489	0.2733	1331	0.3947
4mm	18Hz 0.00674		0.1/0.12/0.15	0.0347	0.1945	6713	0.3335
	19.5hz 0.0086		0.1/0.12/0.15/0.2/0.3/0.4/0.5	0.0398	0.2161	8566	0.3458
	21Hz 0.01043		0.1/0.12/0.15	0.0430	0.2423	10388	0.3729
5mm	22.5hz 0.0118		0.1/0.12/0.15/0.2/0.3/0.4/0.5	0.0466	0.2541	11793	0.3758
	24Hz 0.01345		0.1	0.0489	0.2752	13396	0.3974
	18Hz 0.00691		0.1	0.0356	0.1939	6882	0.3279
6mm	21Hz 0.01033		0.1	0.0427	0.2417	10289	0.3733
	24Hz 0.01336		0.1	0.0481	0.2779	13307	0.4046
	18Hz 0.00693		0.1/0.12/0.15/0.2/0.3/0.4/0.5	0.0357	0.1943	6902	0.3286
	21Hz 0.00982		0.1	0.0417	0.2355	9781	0.3682
	24Hz 0.01335		0.1/0.12/0.15/0.2/0.3/0.4/0.5	0.0481	0.2777	13297	0.4043
							0.3237

2) Experimental results under different materials and thickness

Initial experiments were conducted with the material of fence as the single variable to eliminate the influence of extraneous factors. Model walls were constructed using two distinct wood materials, composite wood and Hinoki wood, ensuring a uniform thickness of 6 mm for all samples. All experiments were performed under identical inflow conditions in a flume test. The experimental results are shown in Figure 5.7. Data points represent observations from three experimental rounds, while the straight line indicates the average of the three rounds and the trend line between points. Different colors denote experiments conducted at seven distinct porosity levels. The porous fence experiments were positioned between points 2 and 3. It can be observed that for each porosity level, the upstream water depth was greater for the Hinoki wood model than for the Composite wood wall, indicating stronger drag resistance from the Hinoki wall. Downstream differences were generally negligible. This demonstrates that experimental material directly influences the results. This difference may be attributed to Hinoki wood being a natural timber with a rougher cross-section than Composite wood, or water absorption results. Consequently, it generates greater frictional resistance within the porous fence's gaps, leading to higher upstream water levels. The underlying mechanism requires dedicated measurements and is beyond the scope of this study. Therefore, subsequent experiments in this study uniformly employed Composite wood with a smoother cross-section. This approach better aligns with the research objective of neglecting pore resistance and focusing exclusively on overall fence resistance, more effectively eliminating the influence of excess pore friction.



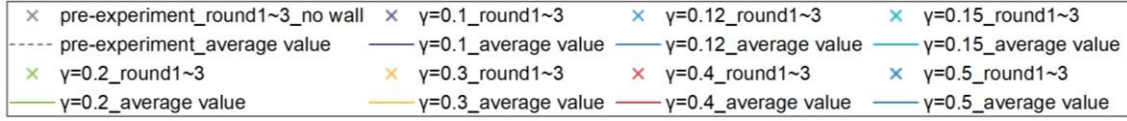


Figure 5.7 Experimental results under different materials (6mm, 10.21L/s)

Then, experiments were conducted with five different wall thicknesses (2 mm, 3 mm, 4 mm, 5 mm, 6 mm) and a uniform porosity of 0.1. These tests were performed at three distinct flow rates to gain an initial understanding of how wall thickness affects the experimental results. Figure 5.8 shows that across the three flow scenarios, the overall upstream and downstream water depth differences were minor. Although the 2mm wall thickness resulted in the greatest upstream water depth, no consistent pattern in water depth emerged for the other wall thicknesses. This leads to a preliminary conclusion: under the uniform Composite wood material, wall thickness does not have a clear impact on the experimental results.

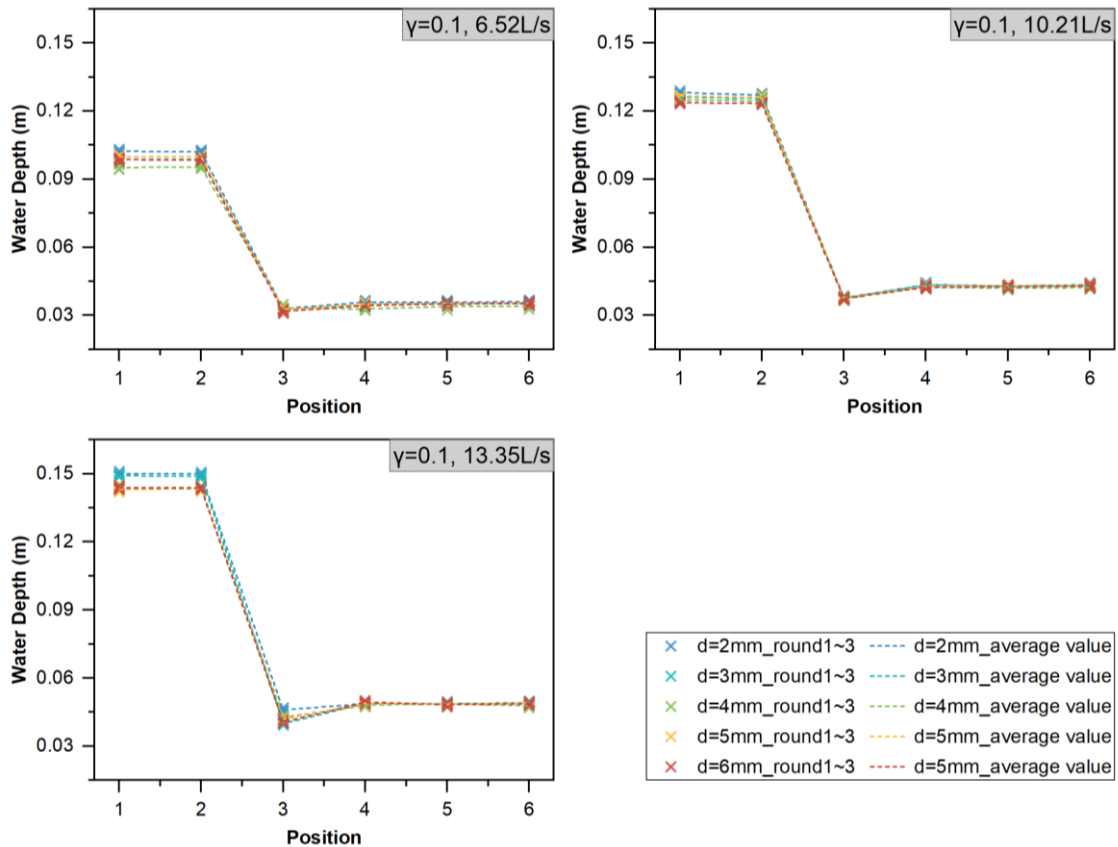


Figure 5.8 Experimental results under different wall thickness ($\gamma = 0.1$)

3) Experimental results and hydraulic performance

Steady-state experiments are designed for hydrodynamic phenomenon analysis,

variable correlation analysis, C_d value calculation, and model validation of steady-state water depth. They primarily involve three wall thicknesses (2 mm, 4 mm, 6 mm) and three inflow rates. These were conducted across seven porosities (0.1, 0.12, 0.15, 0.2, 0.3, 0.4, 0.5). Two additional porosity groups were added between 0.1 and 0.2 based on experimental observations indicating greater fence influence on resistance variation in the low porosity range. Figure 5.9 presents statistical observations for walls of 2mm and 4mm thickness across the three flow rates. Gray represents initial experimental values without walls, while other colors denote experimental values at different porosities. The following hydrodynamic phenomena of porous walls can be analyzed: (i) adding porous fence causes significant upstream water depth changes over a very long influence distance, while downstream water depth shows little difference from the no-fence state, with flow recovering rapidly; (ii) porosity directly affects upstream water depth that higher porosity leads to lower upstream water depth, indicating weaker flow obstruction, which is consistent with conventional understanding; (iii) as inflow velocity increases, upstream water depth rises, while downstream depth remains relatively stable; (iv) downstream water depth decreases only at the very nearby measurement point 3, with this effect becoming more apparent as flow discharge increases.

The unsteady-state experiments aim to analyze hydrodynamic phenomena and validate the model's performance in simulating overall dynamic processes. Hydrodynamic analysis is represented by experiments conducted on a model with a 4mm wall thickness under a fixed inflow rate of 10.21 L/s. Figure 5.10 presents experimental results across seven porosity ranges from 0.1 to 0.5. Red indicates initial experimental values without the fence, black represents the average water depth at upstream measurement points (1 & 2), and gray denotes the average water depth at downstream measurement points (4, 5, 6). Overall, both upstream and downstream flows reach a steady state after a certain period. The following hydrodynamic phenomena of the porous wall can be analyzed: (i) It further confirms that adding the porous wall causes significant changes in upstream water depth while downstream flow recovers quickly; (ii) Although the steady-state water depth downstream shows little difference, the presence of the porous wall significantly delays the arrival time of the downstream flood peak, and this

delay time shortens as porosity increases.

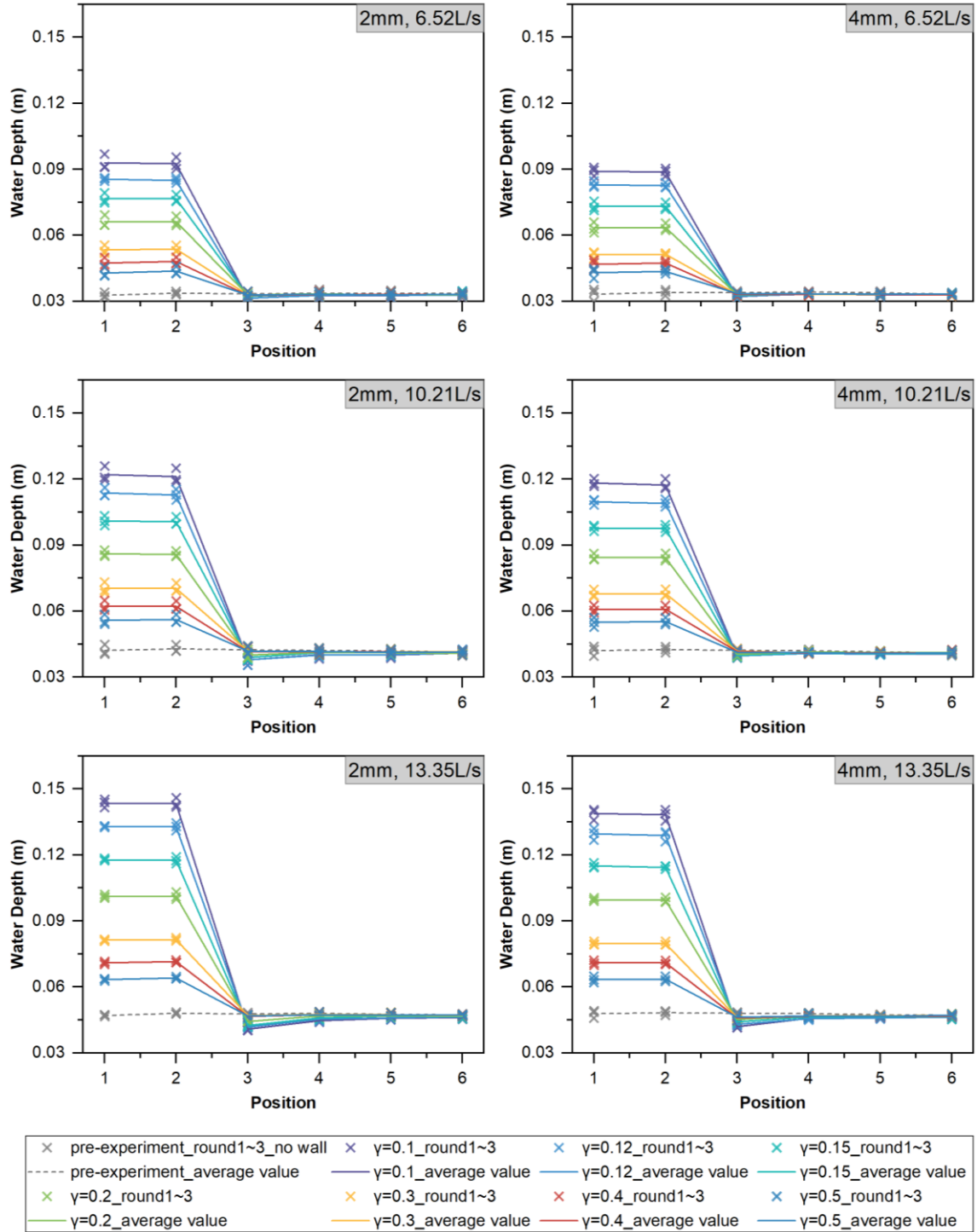


Figure 5.9 Experimental results under steady conditions

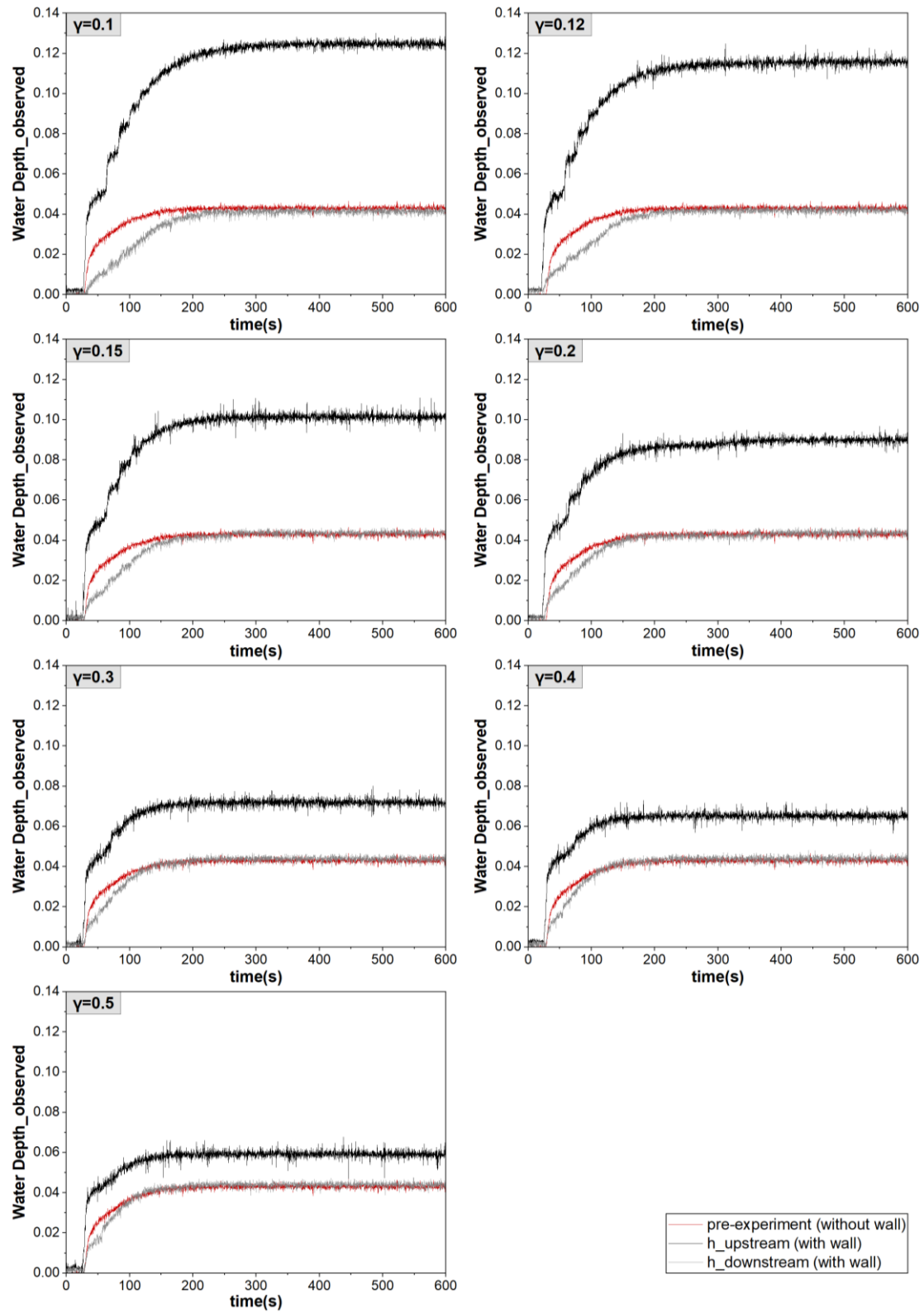


Figure 5.10 Experimental results under unsteady conditions ($d = 4mm$, $Q = 21Hz$)

Summarizing experiments under different flow conditions, the presence of porous fences significantly impacts upstream water depth while exerting limited influence on

downstream water depth. However, they delay the arrival of downstream flood peaks. Porosity exhibits the most pronounced effect on experimental outcomes. From a hydraulic perspective, the core hydraulic characteristics of porous fences center on the structure itself generating additional resistance to the flow, thereby altering the water depth distribution and velocity profile upstream and downstream.

5.2. Empirical equation for the drag coefficient C_d

5.2.1. Calculation method of C_d

In determining the drag coefficient of porous fence, this study employs a two-step approach. First, since the porous wall experiments lacked direct force measurement devices, an equivalent drag force induced by the porous fence is back-calculated from the momentum equation and then used to derive the volume-averaged drag coefficient C_d . A control volume that encloses the porous fence is defined in the flume (Fig. 5.11). Under steady conditions, and by comparing the fenced and unfenced cases under identical boundary conditions, the net change of momentum across the control volume is attributed to the porous fence. Based on the Reynolds Transport Theorem, the equivalent drag force is computed using the measured discharge and the depth-averaged velocities at the upstream and downstream cross-sections. The drag coefficient C_d is then obtained from the drag equation.

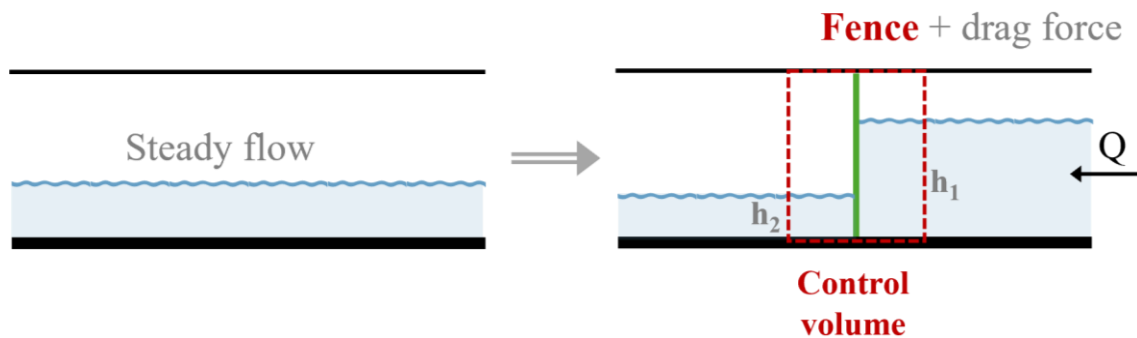


Figure 5.11 Diagram of control volume including porous fence

- 1) Equivalent drag force calculation based on Reynolds transport theorem

Applying the momentum form of Reynolds' transport theorem to the control volume gives Eq. (6):

$$\sum \vec{F} = \frac{d}{dt} \int_{CV} \rho \vec{v} dV + \int_{CS} \rho \vec{v} (\vec{v}_{rel} \cdot \hat{n}) dA \quad (6)$$

where $\sum \vec{F}$ represents the resultant external force acting on the control volume, ρ denotes the density of water, $\vec{v}$ is the velocity vector, CV and CS denote the control volume and control surface, respectively, $\vec{v}_{rel}$ is the relative velocity with respect to the control surface, and $\hat{n}$ is the external normal unit vector. Under steady-state conditions, Eq. (7) holds:

$$\frac{d}{dt} \int_{CV} \rho \vec{v} dV = 0 \quad (7)$$

The control surface is taken as the upstream and downstream vertical cross-sections. Since the pressure-gradient term in the SWEs already accounts for hydrostatic pressure variations, the additional resistance induced by the fence is primarily manifested as momentum loss. Therefore, $\sum \vec{F}$ is treated as the equivalent drag force of the fence F_{fence} (Eq. (8)):

$$\sum \vec{F} = \int_{CS} \rho \vec{v} (\vec{v} \cdot \hat{n}) dA = \rho A_1 v_2^2 - \rho A_2 v_1^2 = \rho Q (v_2 - v_1) = F_{fence} \quad (8)$$

where A_1 and A_2 are the cross-sectional areas at the upstream and downstream sections, v_1 and v_2 are the corresponding depth-averaged velocities, and Q is the discharge satisfying $Q = Av_1 = Av_2$. In the experiment, $A_i = Bh_i$ was obtained using the measured water depths h_1, h_2 and the channel width B , and the depth-averaged velocities were computed as $v_i = Q/A_i$, which enables the determination of F_{fence} .

2) Calculate the drag coefficient based on the drag equation.

The area formed by the porous fence with upstream and downstream water depth measurement points is treated as an equivalent drag volume with effective upstream area A_{ref} . The drag relationship is written as Eq. (9):

$$F_{fence} = \frac{1}{2} \rho v_{ref}^2 C_d A_{ref} \quad (9)$$

where C_d represents the volume-averaged drag coefficient to be determined, A_{ref} denotes the equivalent frontal area, which in this study corresponds to the impermeable wall area of the porous wall, and v_{ref} is the selected reference velocity, typically chosen as the velocity in the undisturbed flow region upstream of the obstacle to represent the initial momentum reference. However, in this study, the porous wall strongly disturbs the

upstream flow, affecting the entire upstream region of the flume. Therefore, v_{ref} employs v_0 , which is the reference velocity obtained from the corresponding unfenced tests under identical boundary conditions. Substituting Eq. (8) into Eq. (9) gives the drag coefficient expression Eq. (10) adopted in this study:

$$C_d = \frac{2Q(v_2 - v_1)}{\rho v_{\text{ref}}^2 A_{\text{ref}}} \quad (10)$$

Accordingly, given the discharge Q , the upstream and downstream water depths h_1 and h_2 (used to compute v_1, v_2), the reference velocity v_0 , and the effective frontal area A_{ref} , the equivalent momentum-loss force and the drag coefficient can be obtained for all test conditions. These results provide the basis for subsequent empirical fitting of C_d .

5.2.2. Univariate analysis of C_d

Before fitting the empirical equation for drag coefficient C_d , univariate analysis based on experimental conditions was conducted to test assumptions about the variables and gain preliminary insight into their correlation with C_d or their general functional trends. Figure 5.12 presents the relationships between C_d and porosity γ , Froude number Fr , Reynolds number Re , and relative plate thickness d/h_0 . For γ , it is observed that across all three flow rates, C_d increases significantly as porosity rises within the 0.1 ~ 0.5 range. The trend remains consistent across flow rates, exhibiting an approximate exponential growth relationship. This indicates that γ is the primary controlling factor influencing C_d . For Fr , under three rounds of tests with fixed porosity and plate thickness, variations in Fr only caused minor fluctuations in C_d within a narrow range, with no discernible pattern. This indicates that within the tested Fr range, Fr has a negligible effect on C_d . For Re , relatively stable and minor differences were observed between curves at different porosities. However, under the same γ , C_d fluctuated only slightly with Re , indicating that viscous effects exerted a weak influence on resistance under experimental conditions. For the relative plate thickness d/h_0 , at a fixed porosity $\gamma = 0.1$, C_d still showed no significant variation with d/h_0 across three different inflow rates, exhibiting only an irregular, slight upward trend. Overall, porosity exerts the most significant influence on the drag coefficient of porous walls, while the effects of flow regime parameters Fr , Re , and relative plate thickness d/h_0 are negligible and exhibit no

discernible pattern.

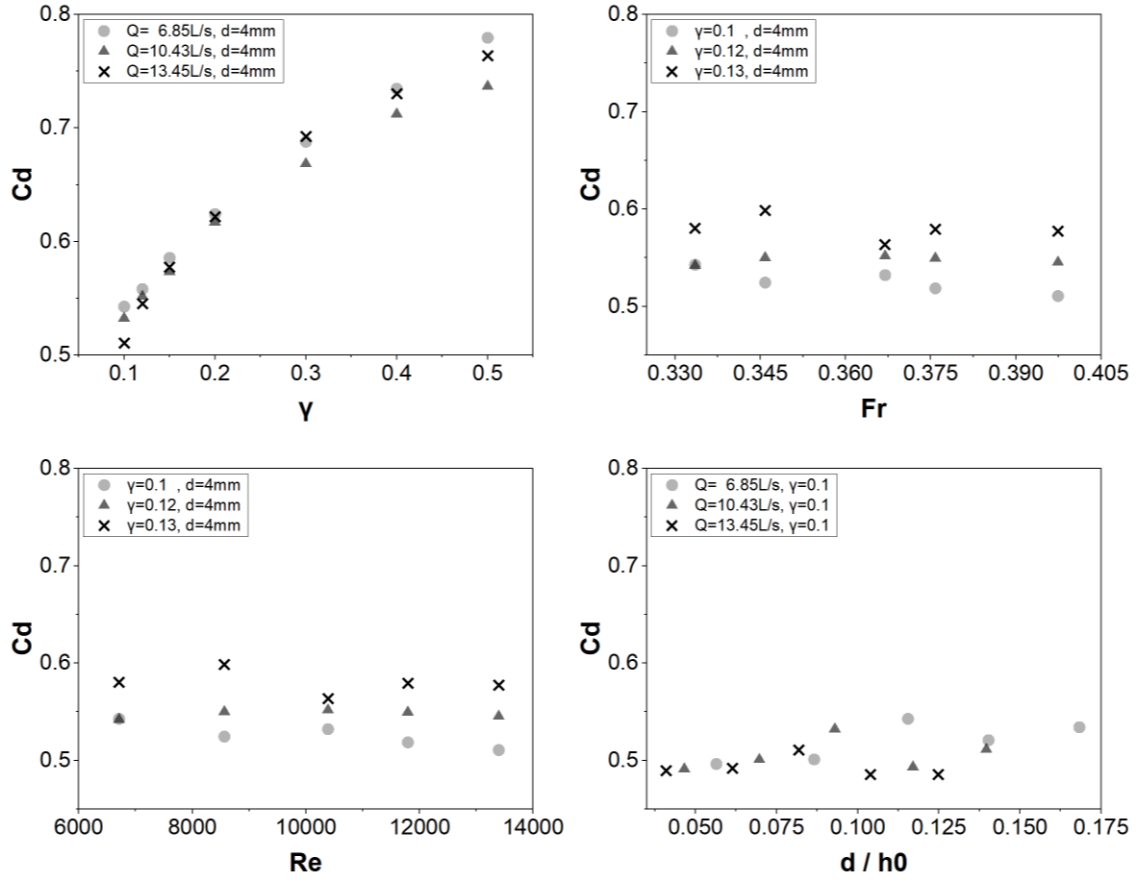


Figure 5.12 Univariate analysis of C_d with γ , Fr , Re , and d/h_0

5.2.3. Empirical equation of C_d

Based on the dimensional analysis conclusions outlined in Section 5.1.2, the volume-averaged drag coefficient C_d of porous fence may be related to dimensionless parameters such as porosity γ , Froude number Fr , Reynolds number Re , and relative plate thickness d/h_0 . To assess the significance of each parameter, Section 5.2.2 first conducts a single-factor analysis of the relationship between C_d and individual variables. Results indicate that within the experimental range, C_d increases significantly and continuously with porosity γ , while exhibiting only slow and irregular fluctuations with variations in Fr , Re , and d/h_0 . This confirms porosity as the dominant factor governing porous fence drag, with other parameters having relatively minor effects.

1) Preliminary fitting of empirical equations

Based on the selected range and definition of independent variables, empirical equation fitting for C_d can be categorized into the following three forms: i. In engineering applications requiring rapid estimation of C_d , it is reasonable to prioritize establishing simplified models using γ ; ii. When comprehensively considering multiple factors, γ , Fr , Re , and d/h_0 can be combined in the fitting equation. In this case, Fr can be represented by Fr_0 , derived from pre-experiments without walls, to reflect the inflow state; iii. Alternatively, Fr can be represented by Fr_1 , the upstream value under the conditions with wall, reflecting the real-time flow state acting upon the wall. Each of these three independent variable selections carries its own reasonable physical significance and explanatory value. The following section compares and analyzes the equations obtained through multiple linear regression for these three independent variable selection modes:

Mode 1: Using 63 sets of steady-state experimental data, with 80% allocated as the training set and 20% as the validation set, nonlinear regression was performed on the different formulas. When only the independent variable γ is selected for fitting, the equation prototype is: $C_d = a\gamma^b$, resulting in the fitted equation Eq. (11):

$$C_d = 0.946\gamma^{0.258} \quad (11)$$

Mode 2: Selecting independent variables γ , Fr_0 , Re , and d/h_0 , the prototype equation for fitting is: $C_d = a\gamma^b Fr_0^c Re^d (d/h_0)^e$. The empirical equation is obtained after fitting:

$$C_d = 0.322\gamma^{0.258} Fr_0^{-0.352} Re^{0.080} \left(\frac{d}{h_0}\right)^{0.005}$$

Mode 2: Selecting independent variables γ , Fr_1 , Re , and d/h_0 , the prototype equation for fitting is: $C_d = a\gamma^b Fr_1^c Re^d (d/h_0)^e$. The empirical equation is obtained after fitting:

$$C_d = 4.197\gamma^{-0.210} Fr_1^{0.641} Re^{-0.105} \left(\frac{d}{h_0}\right)^{-0.022}$$

Based on three preliminary fitting modes (Modes A–C), the study further evaluated their fitting performance separately on the training set (n=50) and an independent validation set (n=13). Results indicate (Table 5.2) that all three approaches demonstrated high explanatory ability on the training set ($R^2 = 0.94831$ – 0.96183) and maintained stable transferability on the validation set ($R^2 = 0.96339$ – 0.96633). Regarding variable

contributions, only γ was statistically significant in both mode A and mode B. The additional variables Fr_0 , Re , and d/h_0 introduced in mode B did not show statistical significance on the training set. In mode C, Fr_1 and Re contributed significantly, while γ and d/h_0 did not reach significance. These findings suggest that while maintaining high fitting accuracy, certain variables within each approach may exhibit either redundant or unstable contributions. Consequently, the next section will conduct multicollinearity analysis to identify unnecessary variables and develop a simplified model with enhanced stability and interpretability.

Table 5.2 Performance of the three primary empirical equations

Method	Predictors (log-linear model)	Training set R^2	Significant predictors in training ($p < 0.05$)	Validation set R^2
A	γ	0.94831	γ ($p = 1.56 \times 10^{-32}$)	0.96339
B	$\gamma, Fr_0, Re, d/h_0$	0.94946	γ ($p = 1.32 \times 10^{-30}$)	0.96473
C	$\gamma, Fr_1, Re, d/h_0$	0.96183	Fr_1 ($p = 3.39 \times 10^{-4}$) Re ($p = 8.12 \times 10^{-4}$)	0.96633

2) Multicollinearity analysis of complete variables

After obtaining preliminary fitting results, to examine the dependency relationships among the dimensionless variables used for fitting and assess the impact of potential multicollinearity on the regression coefficients, this study calculated the Pearson correlation coefficient matrix for the log-transformed variables $\ln C_d$, $\ln \gamma$, $\ln Fr_0$, $\ln Fr_1$, $\ln Re$, and $\ln (d/h_0)$. The results guide subsequent variable selection and equation form adjustments.

The results (Fig. 5.13) indicate significant correlations among some independent variables: i. For mode B, the correlation matrix shows that $\ln Fr_0$ exhibits an extremely strong positive correlation with $\ln Re$ ($r \approx 0.99$), indicating substantial overlap in the information carried by these two variables. Retaining both $\ln Fr$ and $\ln Re$ in the same regression model tends to cause unstable parameter estimates and increased standard errors. Consequently, while the overall fit maintains a high R^2 , some coefficients become insignificant. In contrast, $\ln (d/h_0)$ exhibits weaker correlations with other variables (-0.19843 with $\ln Re$, -0.18544 with $\ln Fr$ and values closer to 0 for others), making it relatively less affected by collinearity. ii. In mode C, $\ln \gamma$ exhibits an extremely strong

positive correlation with $\ln Fr_1$ ($r \approx 0.99$), indicating that the coexistence of these two variables may cause coefficient magnitude, sign, and significance to be sensitive to data fluctuations. On the other hand, the correlation between $\ln Re$ and $\ln (d/h_0)$ is relatively weak ($r \approx -0.20$), suggesting that d/h_0 is relatively independent. iii. Furthermore, the dependent variable $\ln C_d$ also exhibits strong correlation with the independent variables $\ln \gamma$ and $\ln Fr_1$ ($r \approx 0.97$), suggesting that γ and Fr_1 may provide a dominant influence on C_d . Based on these findings, this study optimized the independent variables for mode 2 and mode 3 to enhance parameter stability and improve the clarity of physical interpretations.

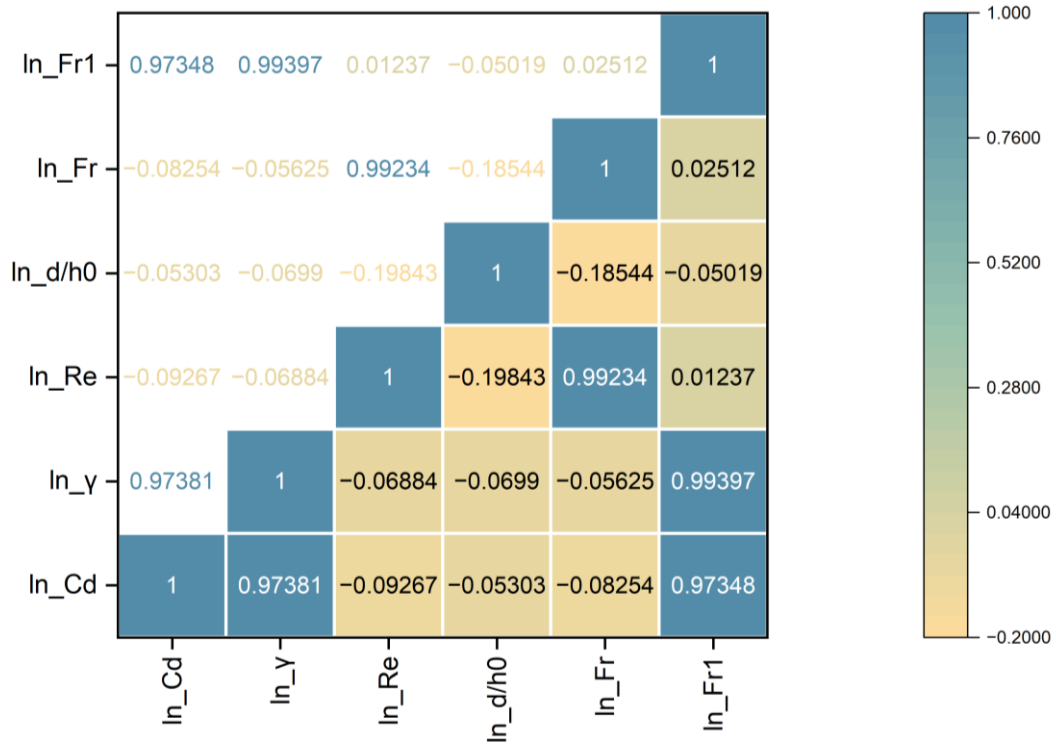


Figure 5.13 Pearson correlation coefficient matrix for logarithmically transformed variables ($\ln C_d$, $\ln \gamma$, $\ln Fr_0$, $\ln Fr_1$, $\ln Re$, $\ln (d/h_0)$)

3) Variable filtering and model optimization

For mode 2, both Fr_0 and Re depend on the inflow discharge in the experiments of this study, resulting in a high correlation between $\ln Fr_0$ and $\ln Re$. Given that Re is sufficiently large throughout the experimental range ($Re > 6000$), this indicates that the flow has reached a fully turbulent state. Consequently, Fr_0 adequately characterizes the relative strength of inertial and gravitational forces and serves as a representative

dimensionless parameter for the hydraulic state. This study retains Fr_0 while removing Re in mode 2, refitting to obtain equation (12):

$$C_d = 0.903\gamma^{0.258}Fr_0^{-0.056}\left(\frac{d}{h_0}\right)^{0.004} \quad (12)$$

For mode 3, the high correlation between $\ln \gamma$ and $\ln Fr_1$ indicated by Pearson analysis is also physically reasonable. Since Fr_1 originates from experimental measurements, it strongly depends on γ and reflects the influence of the wall. Therefore, only one of the two terms needs to be retained. Furthermore, referencing equations (16) and (17) in Section 5.3.1 below, the drag source term expression adopted in this study explicitly incorporates the $(1-\gamma)$ term. The influence of porosity on drag intensity can thus be understood as already embodied within the drag term. Thus, mode 3 retains Fr_1 during optimization to characterize real-time local flow state changes directly affecting the fence, while the geometric effect (γ) remains inherently represented through the $(1-\gamma)$ form in the drag term of the momentum equation. The revised equation (13) for mode 3 is obtained as follows:

$$C_d = 2.292Fr_1^{0.355}Re^{-0.064}\left(\frac{d}{h_0}\right)^{-0.010} \quad (13)$$

4) Comparative evaluation of modified models

Given that all three modification approaches demonstrate exceptionally high predictive consistency on the independent validation set (Validation $R^2 > 0.96$), the comparative results presented in Table 5.3 offer a clear explanation: while all three modes achieve high fitting accuracy on the validation set, they exhibit fundamental differences in underlying causal logic, variable information sources, and parameter stability. Consequently, each possesses distinct physical characteristics and applicable domains.

Table 5.3 Performance of the three primary empirical equations

Method	Predictors	Final form of equations	Training set R^2	Validation set R^2
A	γ	$C_d = 0.946\gamma^{0.258}$	0.94831	0.96339
B'	$\gamma, Fr_0, d/h_0$	$C_d = 0.903\gamma^{0.258}Fr_0^{-0.056}\left(\frac{d}{h_0}\right)^{0.004}$	0.94918	0.96332
C'	$Fr_1, Re, d/h_0$	$C_d = 2.292Fr_1^{0.355}Re^{-0.064}\left(\frac{d}{h_0}\right)^{-0.010}$	0.95927	0.96862

Mode A (γ) forms the simplest baseline model, directly capturing the dominant influence of porosity on the drag coefficient with minimal parameters while maintaining

high fitting accuracy ($R^2 > 0.95$) for both training and validation sets. This approach cannot precisely capture the influence of flow conditions since it disregards Fr or Re , which are difficult to define during the initial simulation stage. However, due to its simplicity, practicality, and independence from inflow parameters, this mode is most suitable for engineering practice. In mode B ($\gamma, Fr_0, d/h_0$), Fr_0 is derived from preliminary experiments and represent for inflow background conditions, independent of wall settings. Therefore, it logically avoids the issue of circular interpretation of C_d between two mutually influencing variables. Nevertheless, Fig. 5.13 also indicates that Fr_0 has indirect influence on flow patterns after wall disturbance, suggesting the equation does not consistently utilize these variables. Consequently, its practical application value is limited. Mode C ($Fr_1, Re, d/h_0$) provides the most comprehensive representation of physical mechanisms and demonstrates the best predictive capability. Fr_1 directly captures the wall's localized, real-time flow obstacle effect, and both Fr_1 and Re exhibit statistical significance ($p < 0.05$) in the fitted equation, indicating clearer statistical support for the model. However, since Fr_1 is continuously changing and difficult to obtain directly, this method is more suitable for scenarios where C_d is updated in real-time based on local flow conditions during shallow water equation computations.

As a supplementary analysis, a comparison between observed and computed values of C_d through three modes (A-C) are shown in Figure 5.14. The horizontal axis represents the measured drag coefficient C_d^{obs} , while the vertical axis shows the predicted value C_d^{pre} calculated using empirical equation Eq. (13). Different symbols denote training set and validation set data, respectively, with surrounding areas marked by solid and dashed lines indicating $\pm 5\%$ and $\pm 10\%$ error bands. Overall, most data points fall within the $\pm 5\%$ or $\pm 10\%$ error bands, indicating that all three correction equations exhibit good predictive accuracy within the experimental range.

Regarding the scatter plot characteristics, in mode A, since the empirical equation uses only porosity γ as an independent variable and γ values in the experiments were discrete points, the predicted values at identical γ values tend to cluster in short horizontal lines. A reasonable conjecture is that these laterally distributed points may stem partly from simplified secondary influences such as Fr , Re , and d/h_0 . In mode B, after

incorporating background variables like Fr_0 , the scatter distribution hasn't shown significant change, suggesting limited improvement from additional variables. In mode C, by introducing Fr_1 which incorporates wall disturbance information, exhibits a more apparent clustering tendency near the 1:1 line, demonstrating stronger mechanism explanatory capability.

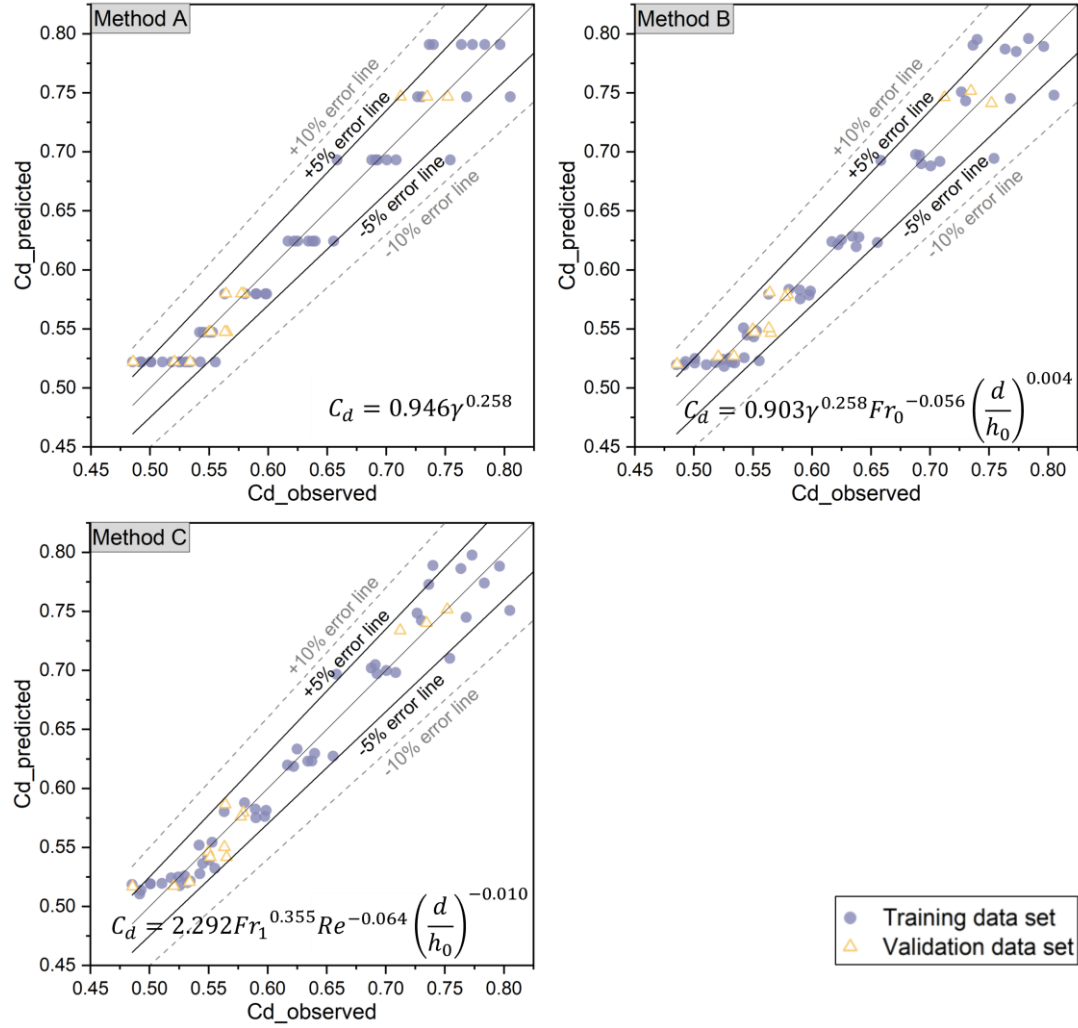


Figure 5.14 Comparison between observed and computed values of C_d

It can be concluded that within the geometric and flow parameters specified in this study, the simplified empirical formula maintains high predictive accuracy while significantly reducing the number of parameters, making it more suitable for engineering calculations and numerical modeling. The following case studies on cultural heritage sites will also employ this simplified approach.

5.3. Modeling extension and validation of porous fence

5.3.1. Development of 2D numerical model

To characterize the hydraulic effects of porous fence in a 2D hydrodynamic model, this study introduces a drag term into the momentum equation of the shallow water equations, drawing on the common treatment of building drag term in urban flood simulations (Fukuoka, 1998). For a fence element at water depth h and with an average cross-sectional flow velocity v , the drag is expressed as Eq. (9) in Section 5.2.1. When this resistance is distributed to a mesh element with area A' , the volumetric forces in the x and y directions can be expressed as Equations (14) and (15):

$$\frac{\tau_{dx}}{\rho} = \frac{1}{2} C_d \frac{L_{fence}}{A'} (1 - \gamma) h |u| u \quad (14)$$

$$\frac{\tau_{dy}}{\rho} = \frac{1}{2} C_d \frac{L_{fence}}{A'} (1 - \gamma) h |v| v \quad (15)$$

Here, L_{fence} represents the planar length of the porous wall within the grid cell, u and v denote the average flow velocities in the x and y directions, respectively, γ is the porosity, and $(1 - \gamma)$ indicates the solid fraction contributing to bearing resistance. For convenience, an equivalent resistance coefficient C'_d at the grid cell scale is introduced, expressed as Eq. (16):

$$C'_d = C_d \frac{L_{fence}}{A'} \quad (16)$$

Expressing the unit-width flow rate as $M = uh$ and $N = vh$, with water level denoted as H , the expanded control equations are expressed as Eq. (17), Eq. (18), and Eq. (19):

Continuity equation:

$$\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \quad (17)$$

Momentum equation:

$$\frac{\partial M}{\partial t} + \frac{\partial (uM)}{\partial x} + \frac{\partial (vM)}{\partial y} = -gh \frac{\partial H}{\partial x} - \frac{gn^2 M \sqrt{u^2 + v^2}}{h^{\frac{4}{3}}} - \frac{1}{2} C'_d (1 - \gamma) M \sqrt{u^2 + v^2} \quad (18)$$

$$\frac{\partial N}{\partial t} + \frac{\partial (uN)}{\partial x} + \frac{\partial (vN)}{\partial y} = -gh \frac{\partial H}{\partial y} - \frac{gn^2 N \sqrt{u^2 + v^2}}{h^{\frac{4}{3}}} - \frac{1}{2} C'_d (1 - \gamma) N \sqrt{u^2 + v^2} \quad (19)$$

Unlike methods that treat buildings as porous media in urban flooding, the porous fence in this study is numerically represented as mesh boundaries within the mesh. Their physical thickness is far smaller than the mesh scale, occupying no unit volume directly

and reducing no flow area. Therefore, no additional porosity factor is introduced in other source terms. The influence of the porous fence is reflected solely through the drag term in the momentum equation mentioned above.

Unlike methods that treat buildings as porous media in urban flooding, the porous fence in this study is numerically represented as mesh boundaries within the mesh. Their physical thickness is far smaller than the mesh scale, occupying no unit volume directly and reducing no flow area. Therefore, no additional porosity factor is introduced in other source terms. The influence of the porous fence is reflected solely through the drag term in the momentum equation mentioned above.

In summary, this study constructs an improved 2D numerical model within the SWEs framework by incorporating an additional momentum loss term, suitable for local regions featuring porous fence elements. The hydrodynamic effects of porous fence on the fluid are parameterized using the empirical relationship $C_d(\gamma)$ derived from steady-flow experiments. To validate the reliability of this extended model and C_d , Sections 5.2.2 and 5.2.3 below will respectively compare numerical simulation results with experimental observations under steady-flow and unsteady-flow conditions.

5.3.2. Validation under steady conditions

After completing the model extension and empirical equation fitting for the resistance coefficient, this subsection first validates the extended model incorporating the new drag term under steady flow conditions to verify its ability to accurately reproduce the steady-state water levels observed in experiments under various operating conditions. Figure 5.15 displays the steady-state water depths upstream and downstream of the porous wall as a function of porosity γ for different combinations of wall thickness (2 mm and 4 mm) and inflow discharge (6.52, 10.21, 13.35 L/s), along with the relative error between simulated and observed values. Black indicates upstream values, red indicates downstream values, and hollow and solid points represent observed and simulated values, respectively.

Overall, numerical models effectively reproduce the fundamental hydraulic effects of porous fence: as porosity decreases, the resistance to flow increases, resulting in a

significant rise in upstream water depth and a slight decrease in downstream water depth. Under varying inflow discharge and wall thickness, the shapes of the upstream-downstream water depth versus porosity curves align closely with field measurements. This indicates that drag coefficient calibration based on γ reasonably reflects the head loss of porous fence under steady-state conditions. Specifically, simulated upstream water depths generally fall slightly below measured values, with relative errors ranging from -2% to -10% under most operating conditions. These errors exhibit slight enlargement as porosity increases, indicating a minor underestimation of head loss caused by porous fence, though the overall deviation remains limited. Downstream errors were smaller, predominantly within the range of -5% to +3%, indicating the model reliably captures the influence of porous walls on downstream steady water levels. Table 5.4 demonstrates the numerical model's performance when incorporating resistance terms under steady-state simulation conditions.

Table 5.4 Results of the Validation under steady conditions.

Porosity (γ)	0.1	0.12	0.15	0.2	0.3	0.4	0.5	Average	Total
RMSE	0.003	0.003	0.004	0.004	0.005	0.004	0.004	0.004	0.004

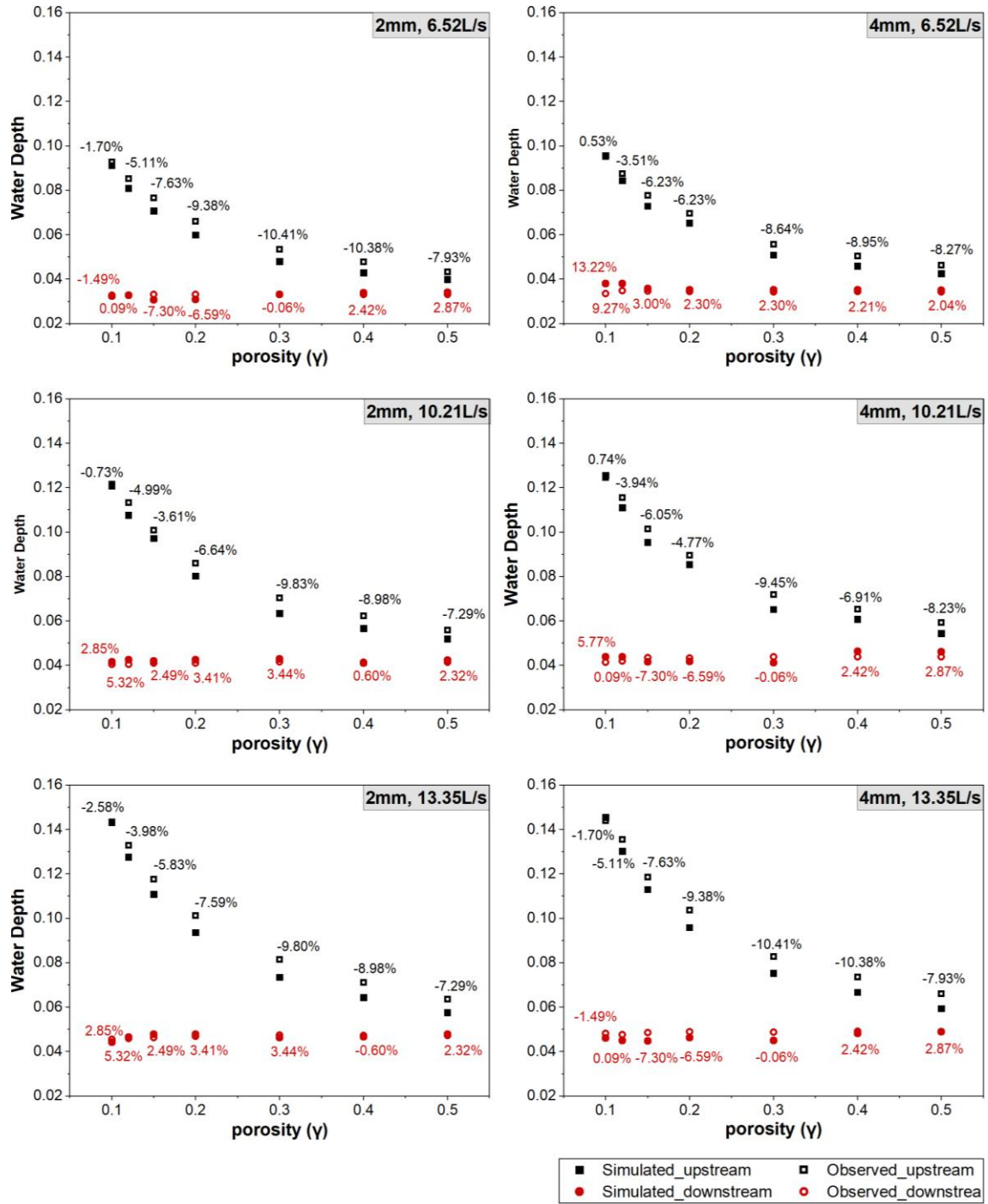


Figure 5.15 Simulated vs. observed under steady condition (with relative error).

It can be observed that the error levels across different wall thickness and flow rate combinations are relatively close, indicating that the unified empirical drag coefficient equation $C_d(\gamma)$ demonstrates good applicability to variations in wall thickness and flow rate. Further statistical analysis reveals that the overall RMSE for all steady-state

conditions combined is 0.004m, indicating that the model can nearly accurately reproduce water depth values during steady-state conditions. In summary, under steady-flow conditions, the experimentally fitted $C_D(\gamma)$ and the resistance source term introduced for SWEs reliably describe the influence of fences with varying porosities on water flow. This provides a steady-state calibration foundation for subsequent application during unsteady flood processes.

The purpose of steady-state verification is to prioritize testing whether the newly introduced drag terms can accurately reproduce the balanced water level without introducing temporal variations. Only upon reliably reproducing steady-state numerical results can the applicability of the model during unsteady flood processes be further discussed. This also serves as the starting point for the subsequent subsection on unsteady condition validation.

5.3.3. Validation under unsteady conditions

Building upon steady-state validation, this section further examines the model's ability to simulate flood processes under unsteady flow conditions. Figure 5.16 compares simulated and observed water depth profiles upstream and downstream for porous walls with the same wall thickness (4 mm) and flow rate (10.21 L/s), but varying porosity values ($\gamma = 0.10 \sim 0.50$) across seven groups. The gray curve represents observed water depth, with data oscillations indicating high-frequency fluctuations caused by probe signals; the purple curve shows the numerical simulation results.

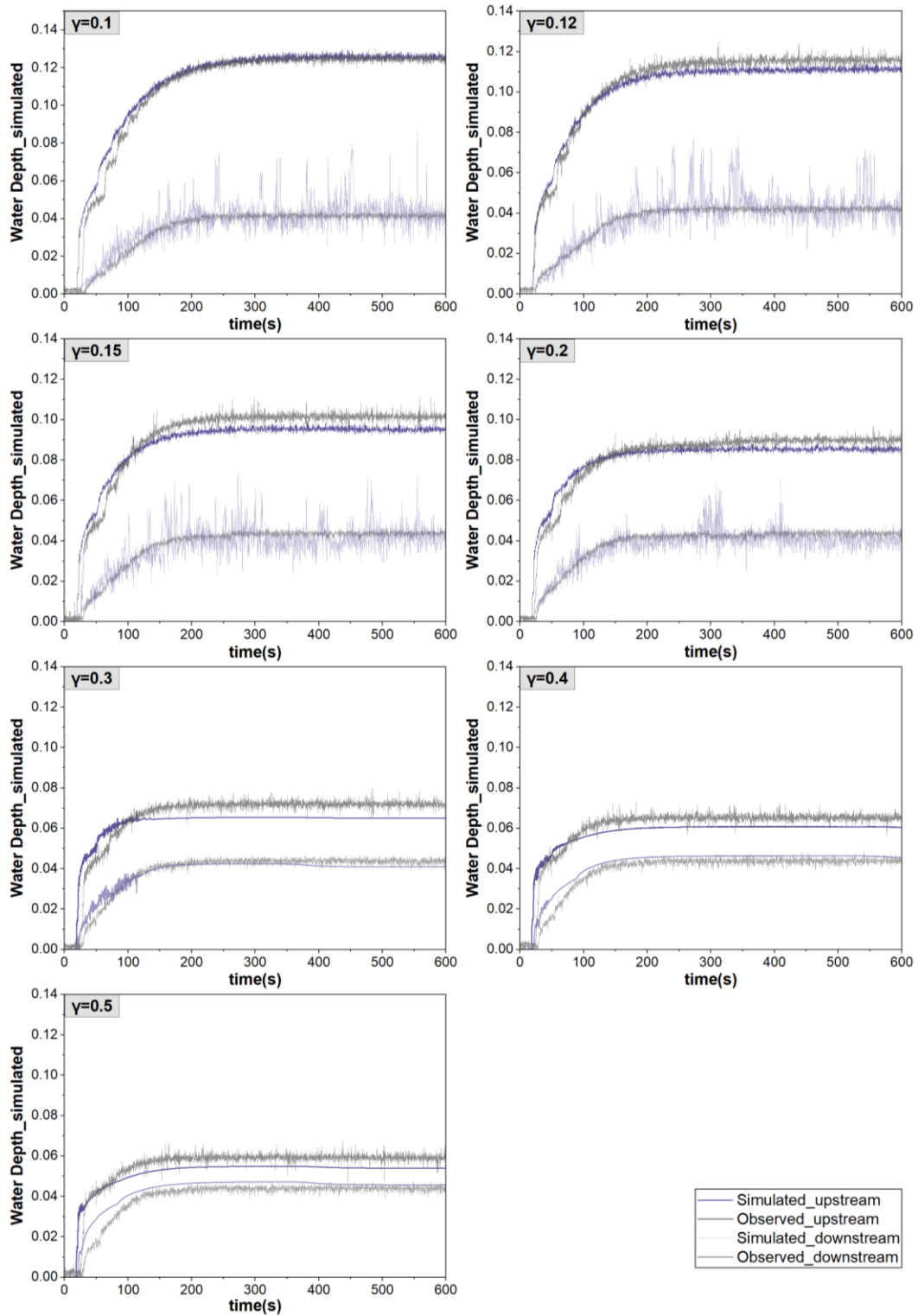


Figure 5.16 Simulated vs. observed results under unsteady conditions (4mm, 10.21L/s)

As can be observed, the model effectively replicates the temporal evolution of water depth across all porosity conditions: following the inflow onset, both upstream and

downstream water levels exhibit a pattern of rapid rise followed by gradual stabilization. However, the simulated rise slope is slightly sharper than the observed values. This deviation is likely attributed to the fixed C_d value derived from steady-state experiments being slightly higher than the true C_d during the water depth rise phase, though the error range remains small. Consistent with steady-state results, lower porosity correlates with higher upstream water levels and lower downstream water levels. This trend persists throughout the entire evolution process, indicating that the C_d calibrated from steady-state experiments remains valid under unsteady conditions. Table 5.5 presents the performance metrics of the numerical model under unsteady simulation conditions.

Table 5.5 Results of the Validation under steady conditions.

	Porosity (γ)	0.1	0.12	0.15	0.2	0.3	0.4	0.5	Average
Up- stream	RMSE(m)	0.006	0.005	0.007	0.005	0.008	0.006	0.006	0.006
	NSE	0.968	0.970	0.921	0.935	0.785	0.831	0.792	0.886
	Porosity (γ)	0.1	0.12	0.15	0.2	0.3	0.4	0.5	Average
Down- stream	RMSE(m)	0.008	0.008	0.006	0.006	0.003	0.004	0.004	0.006
	NSE	0.622	0.491	0.704	0.729	0.931	0.891	0.849	0.745

From a quantitative perspective, the average RMSE for both upstream and downstream regions under unsteady-state conditions is 0.006m, corresponding to NSE values of 0.886 and 0.745, respectively. The NSE metric indicates that the upstream model demonstrates superior reproducibility compared to the downstream region, exhibiting higher accuracy particularly at low porosities. Deviations are primarily concentrated in the downstream region, potentially due to two reasons: first, the shallower water depth downstream makes relative errors more sensitive; second, in numerical simulations, the additional drag term is applied as a source term concentrated along the mesh boundary of the porous fence. This abrupt treatment of local momentum loss may introduce numerical fluctuations after discretization, thereby amplifying fluctuations in

downstream water depth. However, since the primary influence of the porous fence occurs in the upstream section, and flood-related porous fence commonly used in real-world scenarios typically employ walls with lower porosity to enhance functionality, the experimental intervals with larger errors do not impact the practical application of this study.

Compared to steady-flow validation, unsteady-flow validation aims to test whether the model can accurately reproduce flood spread processes while assuming a constant drag coefficient C_d . Results indicate that the improved 2D model not only provides reasonable head losses under steady-state conditions but also maintains good predictive capability throughout the entire process of gradually increasing inflow until stability is reached. This demonstrates that, within the parameter range of this study, the porosity-based drag coefficient can be reliably applied to simulate local flow fields with porous fence structures in practical urban flood scenarios.

5.4. The impacts of porous fences on heritage sites

5.4.1. Spatial arrangement and parameter settings of porous fence

The extended 2D inundation model incorporating drag terms from porous walls was similarly applied to Shimogamo Shrine and Katsura Imperial Villa along with their surrounding areas. The fence at Shimogamo Shrine comprises outer solid fence of varying heights and an inner composite fence, where the lower section consists of a solid fence of a certain height topped by a porous fence. In the numerical simulation, when water depth exceeds the solid portion, calculations switch to the new porosity value of the porous fence. The southern boundary of Katsura Imperial Villa features a solid fence, completely separating it from the modern residential area. The northern Hogaki and eastern Katsuragaki are both constructed from dense bamboo arrangements. The Katsuragaki, covered with woven live bamboo, has an actual porosity lower than 0.1. Since handcrafted porous fence models in experimental studies cannot precisely replicate walls with porosities below 0.1, hydraulic parameters corresponding to 0.1 were temporarily used in actual simulations. This approach also allows for a safety threshold in heritage risk

protection. In subsequent numerical simulations, distinct values were assigned to fences with varying parameters across each case (Fig. 5.17), and the validated modified model was applied for inundation simulations.

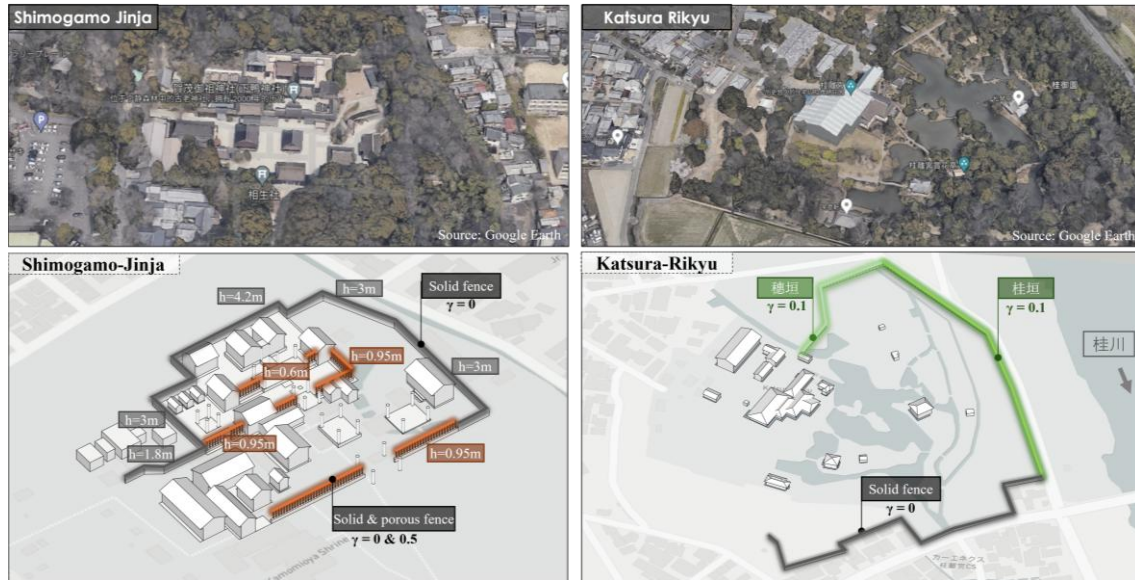


Figure 5.17 Spatial arrangement and parameter settings of porous fence

5.4.2. Necessity of representing fence in flood modeling

In both study areas, simulations were conducted for two scenarios: Scenario A, which considers different porosity levels of existing fences based on current conditions, and Scenario B, which assumes the absence of such vertically negligible barriers. Scenario B mirrors standard practices for flood simulations in large urban areas. This comparative analysis further confirms that considering walls with varying porosity is essential for small-scale localized flood simulations, particularly for heritage sites.

The overall simulation results for Shimogamo Shrine and its surrounding areas closely resemble those presented in Section 4.3.2 when comparing simulations with and without piloti. Therefore, we will not present them again here. The reason is evident: minor adjustments to local site structures or obstacles at vastly different scales typically do not significantly impact the overall results. This indirectly validates the rationality of neglecting local architectural features in large-scale scenario simulations. However, the significant impact of these features on local flood behavior further underscores the

necessity of developing refined simulation models for heritage sites. Focusing on the core buildings of Shimogamo Shrine, the two simulation scenarios again reveal distinct spatial differences. Figure 5.18 shows an enlarged comparison: In Scenario A, the presence of the fence significantly reduces water depth within the courtyard while increasing it outside the walls. The maximum water depth lines closely align with the fence boundary, demonstrating the fence's direct impact on inundation outcomes. Particularly in the second courtyard (north side) with two layers of fencing, most areas remained dry. In contrast, in Scenario B (without fencing), flood distribution across the site varied with topography.



Figure 5.18 Maximum water depth of the center heritage area at Shimogamo-Jinja

The overall simulation results for Katsura Imperial Villa and its surrounding areas also show no significant variation. Focusing specifically on the core building complex of Katsura Imperial Villa (Fig. 5.19), the spatial differences in water depth between Scenario A (considering the porous fence) and Scenario B (assuming no fence exists) are not significant. In specific numerical terms, water depth is slightly higher in Scenario A. Considering the location of the breached embankment indicated in Figure 4.10 relative to Katsura Imperial Villa, along with the spatial layout of the porous fence shown in Figure 5.15, a reasonable explanation for this phenomenon is that Katsura Imperial Villa is situated upstream of the fence in most current urban flood prediction scenarios. According to the experimental observations of porous fences explained in Section 5.1.3, increased

water depth upstream is a key hydraulic effect. Additionally, due to Katsura Imperial Villa's garden-style spatial layout, the fence is positioned relatively far from the core structures, diluting its hydraulic effectiveness.

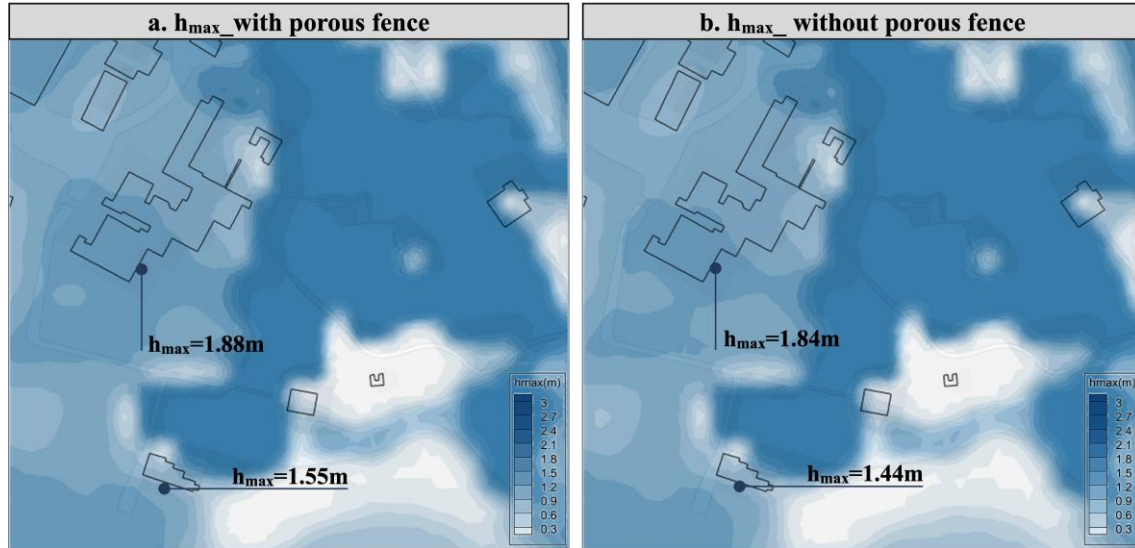


Figure 5.19 Maximum water depth of the center heritage area at Katsura-Rikyu

Simulation results from both sites demonstrate the high sensitivity of localized flood behavior to different configurations of porous fences. This indicates that when conducting inundation simulations for cultural heritage sites, incorporating resistance terms within SWEs to accurately represent the influence of spatial structures like fences on flood behavior constitutes another critical component of refined modeling for cultural heritage protection.

5.4.3. The hydrodynamic mechanism of flow through porous fence

This section begins with a comparative analysis of flow field simulation results from two case studies to further examine and understand the hydrodynamic mechanisms of porous fences. From the maximum water depth comparison in Subsection 5.4.2, we can preliminarily recognize that the presence of fences produced different effects on the two cases. Three primary influencing factors may be identified: First, the solid fence component constituted a significant proportion in the Shimogamo Shrine fence, likely playing a dominant role; Second, the distinct spatial configurations of the two heritage sites, like open spaces versus enclosed spaces, led to considerable differences in the

fence's influence range; Third: The relationship between the inflow direction and the porous fence layout may have influenced the results. These three factors will be further explained in the flow field analysis of each case.

Numerically, all 12 representative observation points within the site indicate that water depth and flow velocity are significantly reduced when porous fence are present compared to the no-fence scenario. Correspondingly, the flow rate also decreases, demonstrating that water entering the protected area through the fences is effectively mitigated (Fig.5.20). Figure 5.21 displays the local maximum flow velocity and peak flow field information at Shimogamo Shrine. Comparing Figure 5.21a and b reveals that the maximum velocity contour lines are directly related to the fence layout. Flow velocities within the fence are generally lower than those outside it, whereas without the fence, the velocity distribution is relatively uniform. Figure 5.21c directly shows that the flow does not pass through the fence. This is because the incoming flow primarily comes from the east and west sides. Specifically, the site becomes the downstream side of the fence, with the solid fence completely blocking the flow on the east side and the buildings on the west side creating most of the obstruction. Of course, under these boundary conditions, the flood depth is insufficient to breach the walls, and the fences are assumed to be sufficiently stable.

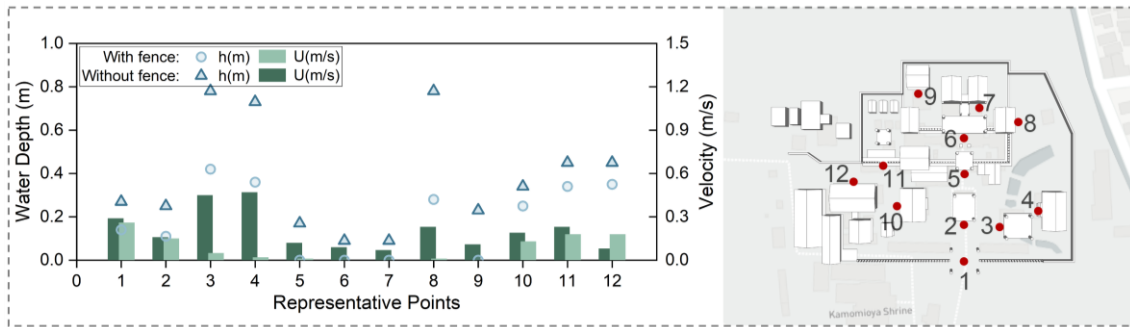


Figure 5.20 Comparison of water depth and velocity at Shimogamo-Jinja

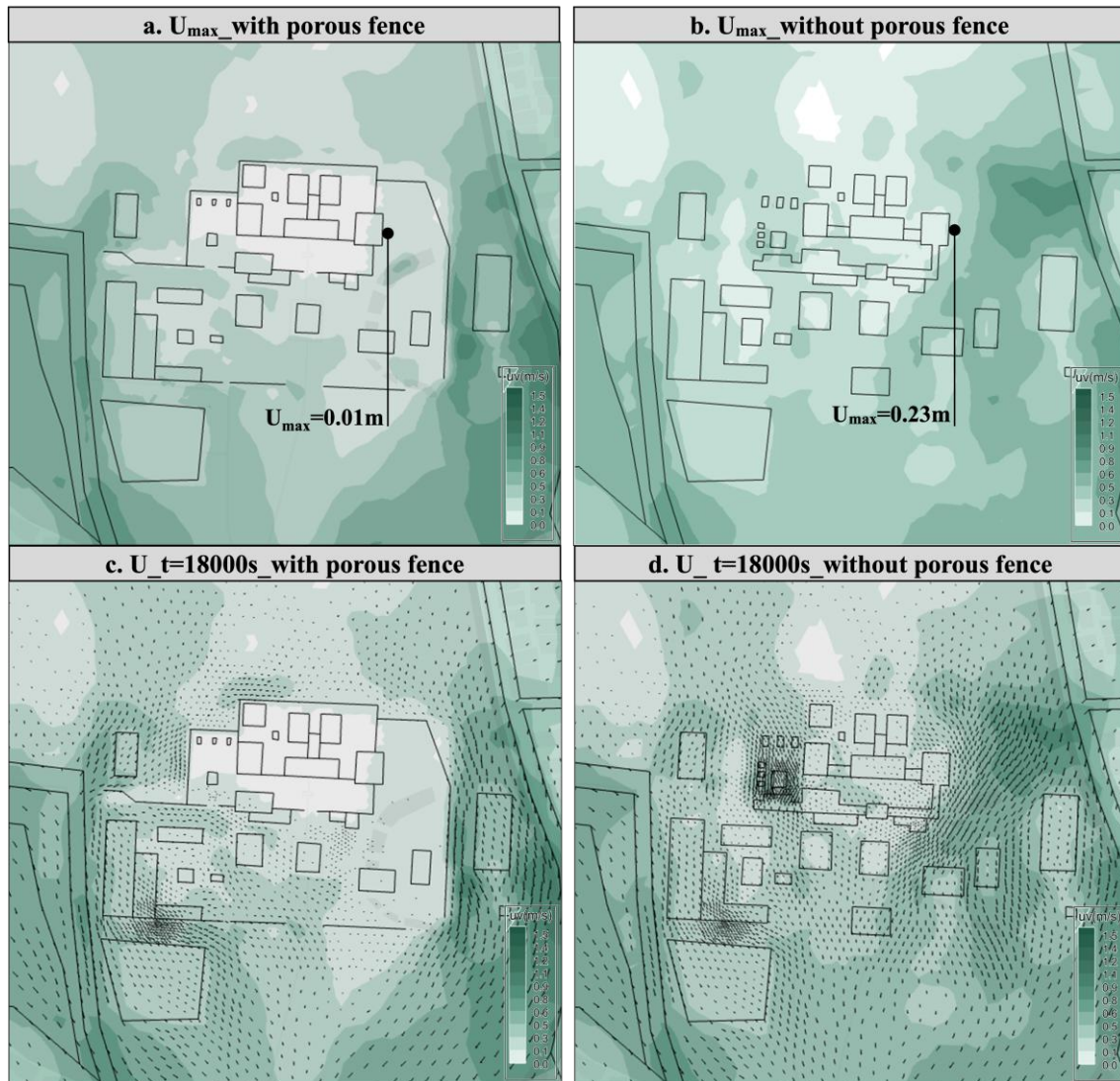


Figure 5.21 Flow velocity of the center heritage area at Shimogamo-Jinja

Unlike the situation at Shimogamo Shrine where the external fence obstructed water flow, simulations at Katsura Imperial Villa showed that the porous fence did not significantly reduce the total inflow into the garden. Since the simulated inflow primarily originated from the northwest while the porous fence was located in the southeast, Katsura Imperial Villa became the upstream side of the fence. The flood process in Figure 5.22 demonstrates that the peak rise slightly, and there are no obvious time delay effects at the peak arrival time. Meanwhile, the flow velocity exhibited increases to some extent (Fig. 5.23a & b). These indicate that Katsura Imperial Villa's existing fence layout does not intercept incoming flow but instead exhibits slight retention effects, reflecting the upstream elevation effect observed experimentally at the actual site scale. The result

arises from both the fundamental differences between solid and porous fences and the relationship between the incoming flow direction and fence orientation. Furthermore, analysis of peak flow times and flow fields at $t=18000$ s reveals limited changes in primary flow paths and overall direction under both conditions (Fig. 5.23c & d), as the porous fence inherently permits water passage. Comparisons of representative observation points also indicate minimal overall variations in water depth and flow velocity (Fig. 5.24). This result may be related to the significant horizontal distance between the porous fence and the core building complex, where hydrodynamic disturbances have significantly attenuated during transmission, thus limiting their influence on the central area. Based on the comprehensive numerical simulation results, it can be concluded that the existing fence at Katsura Imperial Villa does not enhance flood safety within the heritage area under the simulated flood scenario. Instead, due to the hydrodynamic response mechanism of upstream water level elevation, water depth slightly increases across most of the heritage sites, thereby increasing flood risk.

In future work, we will extend the simulations to a historically possible scenario in which floodwater directly enters the site from the Katsura River. This comparison will help clarify whether the existing bamboo fence could provide meaningful interception under different scenarios and further quantify the sensitivity and severity of layout effects.

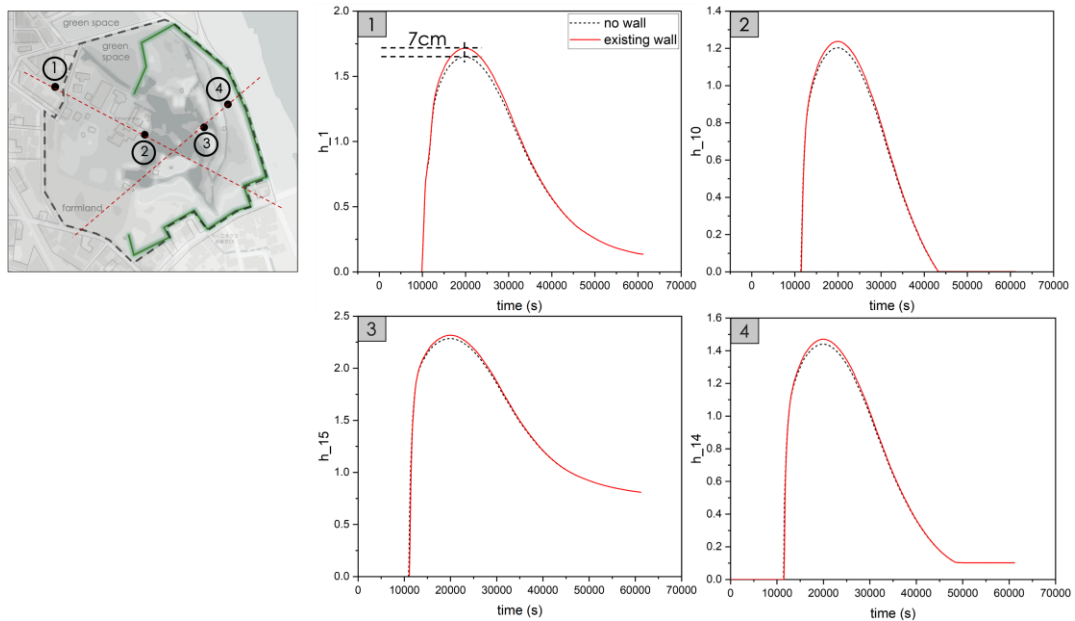


Figure 5.22 Inundation process of the scenarios of no fence and existing fences.

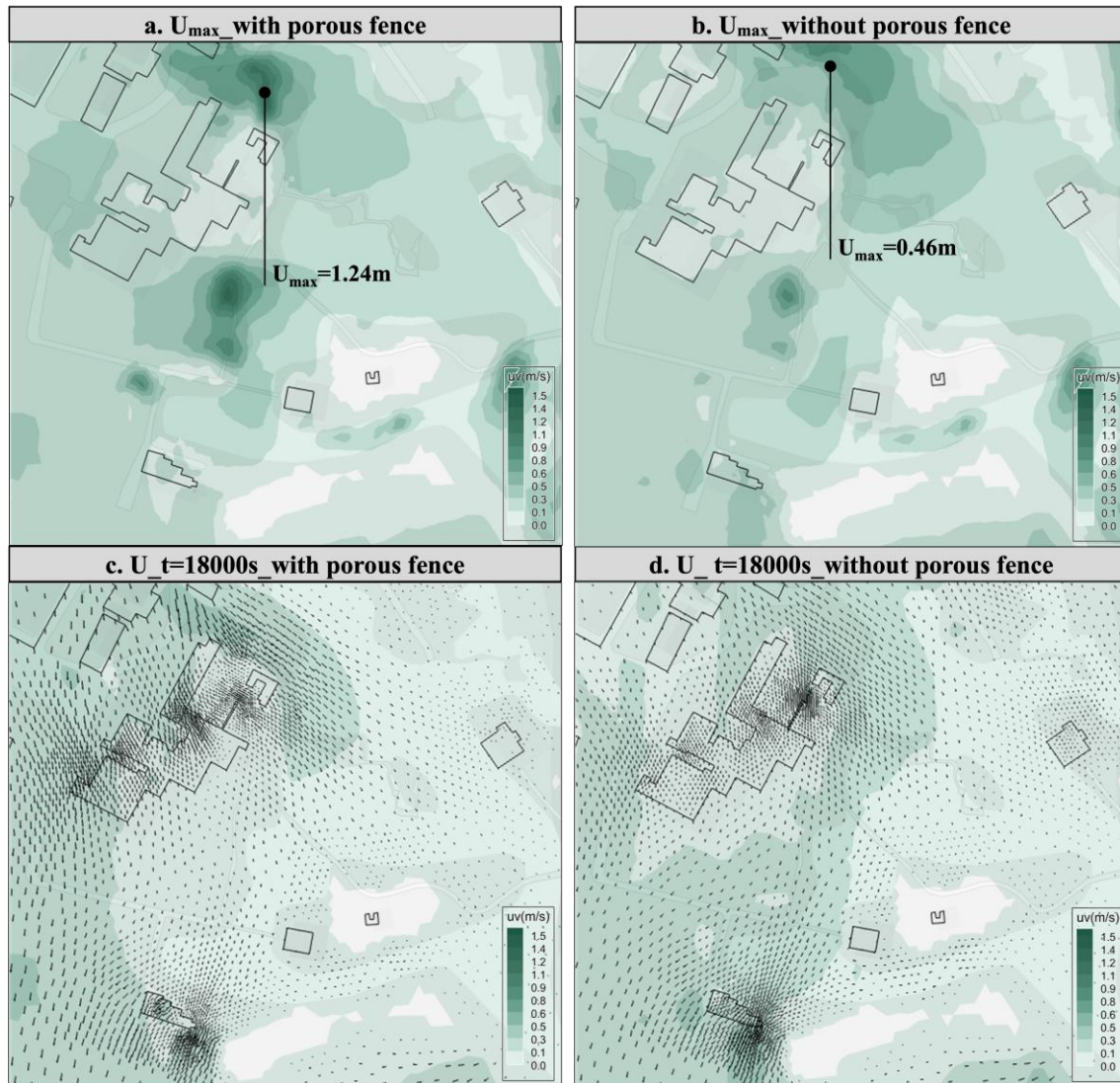


Figure 5.23 Flow velocity of the center heritage area at Katsura-Rikyu

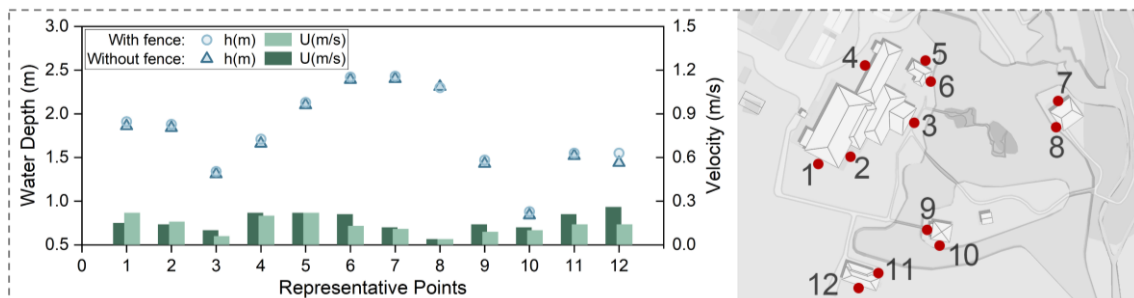


Figure 5.24 Comparison of water depth and velocity at Katsura-Rikyu

Furthermore, for porous fences, an increase in the upstream–downstream water level difference (ΔH) generally implies a higher hydraulic action on the fence, which may directly challenge its structural stability. These implications suggest that the protective

performance of porous fences should be evaluated together with structural checks, rather than relying only on changes in water depth indicators. Further calculations of flood-induced forces and related stability assessments are therefore of practical engineering significance.

5.5. Summary

1) This chapter incorporates a porous fence drag term into a 2D hydraulic model, successfully reproducing key hydraulic characteristics observed in flume experiments: an upstream water level rise, limited impact on downstream water levels, and delayed peak arrival time. The empirically fitted C_d equation demonstrates strong engineering applicability. Although the method of applying resistance concentrated at the extended boundary induces local fluctuations downstream in numerical simulations, its ability to accurately reproduce average values and trends remains highly valuable for practical applications.

2) Two heritage case studies demonstrate that it is essential to account for vertical structural barriers, such as fences, in flood numerical simulations at the heritage scale. Existing fences significantly redistribute the spatial distribution of surface water depth and flow velocity, thereby altering the risk levels for heritage structures. Neglecting these structures can lead to underestimating or misjudging the inundation extent and risk classification of core buildings.

3) The mechanism by which porous fence influence floods essentially involve reconfiguring the spatiotemporal distribution of floodwater: while upstream peak elevation comes at a potential cost, the potential benefit lies in locally reducing water depth and delaying peak spread, thereby creating a time window for emergency flood mitigation efforts. In the Shimogamo Shrine case, the enclosed structure near the buildings, which have a high proportion of solid sections, directly intercepted most of the floodwater. However, such rigid measures could lead to more severe consequences if breached. At Katsura Imperial Villa, the porous fence located farther from the buildings and its layout relative to the mainstream flow direction are contrary to the villa's flood control requirements, failing to provide disaster prevention safeguards. From experimental insights, porous walls combine hydraulic regulation capabilities with

ecological and aesthetic attributes, making them highly suitable as low-intervention measures in cultural heritage flood mitigation design. However, these two cases do not directly provide empirical support for this conclusion. Whether porous fences can effectively reduce or delay flood peaks near critical structures requires further design and testing, which will be explored in Section 6.2 of this paper.

6. Traditional Countermeasures Evaluation and Optimization Design

It is worth considering that many surviving heritage sites located in floodplains embody climate-adaptive design wisdom, such as building on elevated ground, raising structures, and employing overhanging eaves. These traditional passive flood control measures have long enabled heritage sites to coexist with natural hazards, demonstrating their effectiveness in mitigating conflicts between humans and water (Blavier et al., 2023; Liao et al., 2016; Okubo, 2016). However, contemporary environmental shifts and climate change have pushed flood intensity and frequency beyond historical thresholds. Urban development has led to increased surface hardness and narrowed river channels, thereby altering regional hydrological cycles. The traditional disaster resilience advantages of heritage sites are gradually eroding, making it difficult to adequately address flood threats under new climate paradigms and evolving urban built environments (Ali Sargazi and Tahbaz, 2022; Blavier et al., 2023; Chowdhoree and Das, 2022; Ozarisoy and Altan, 2021). Following the comprehensive theoretical and experimental understanding of the hydrodynamic effects of traditional passive flood-adaptive measures, their actual flood reduction effectiveness in real heritage sites urgently requires scientific analysis and comprehensive evaluation. Identifying appropriate intervention measures to enhance the flood resilience of heritage sites will also provide direct recommendations for heritage conservation efforts. This work not only enhances heritage protection efficacy but also extracts adaptable resilience design principles, shifting from a flood control approach to a flood adaptation framework (Aste et al., 2019; Bodach et al., 2014; Liao et al., 2016; Priavolou, 2025; Smith et al., 2023), thereby increasing heritage resilience and future urban resilience through design method.

6.1. Framework of comprehensive effectiveness index

Previous studies have lacked investigations into the mechanisms of traditional flood mitigation measures, and corresponding methods for evaluating their effectiveness also present gaps. To quantitatively assess the impact of traditional passive flood-adaptive measures on the flood resilience of heritage areas, this study concludes by developing a Comprehensive Effectiveness Index (CEI). Specifically, for each flood control structure,

the resilience measure's flood mitigation effectiveness is comprehensively evaluated by comparing key hydraulic parameters across two scenarios. Scenario A (with countermeasures) reflects the actual spatial layout and form of heritage buildings, while Scenario B (without countermeasures) serves as a virtual reference scenario assuming these measures are absent. Using the change between Scenario A and Scenario B as the effect indicator, the CEI evaluates resilience from landscape and architectural dimensions. It combines assessments based on three core hydraulic indicators for each dimension, ultimately integrating values from both dimensions to quantify the overall effectiveness of measures for the heritage zone.

6.1.1. Selection of evaluation indicators

The CEI in this study employs three indicators, selected for systematicity, representativeness, and quantifiability: maximum inundation depth Difference ($\Delta h_{\max}$), functional exposure duration Difference ($\Delta T_{\exp}$), and depth-duration integral Difference (ΔDDI). These indicators cover three theoretically complementary dimensions: peak severity, inundation period, and cumulative intensity. All of them can be computed directly from numerical models' outputs. In combination, these indicators offer a concise, comprehensive, and reusable basis for evaluating flood mitigation effectiveness. The following paragraphs will describe each indicator:

1) $\Delta h_{\max}$ is a peak severity indicator defined as the difference between maximum water depths under different scenarios. This indicator represents the peak hydrostatic pressure of a flood and is directly related to physical damage such as structural stability and object buoyancy (Liou and Hoang, 2024; Wing et al., 2020). It is used to evaluate the capacity to reduce the immediate maximum destructive force of floods, focusing on objective changes in hydraulic characteristics.

2) $\Delta T_{\exp}$ is the persistence indicator, defined as the difference in total exposure time based on functional disruption. It represents the duration of inundation and exposure and is directly related to functional stability and disruption (De Bruijn et al., 2019; Pinel et al., 2020). It measures how well countermeasures work to shorten the total time that a system is under flood stress, with a focus on the subjective value of functional protection. To

emphasize protection of the structure itself, this indicator uses differentiated thresholds: for building areas, the threshold is the height of the first habitable floor (piloti height); for landscape areas, a threshold of 0.05 m represents the critical depth at which normal activities can recover (MLIT, 2017), thereby filtering insignificant water accumulation.

3) ΔDDI is a cumulative intensity indicator. It represents a novel composite hydraulic metric increasingly gaining attention for evaluating flooding by integrating water depth and duration (Mugume et al., 2015; Wu et al., 2020). It is defined as the difference in depth-duration integrals in different scenarios. This indicator correlates with the hidden long-term damage, such as soaking damage and material degradation. It is used to measure the reduction of cumulative effect while also focusing on the objective changes in hydraulic characteristics. The overall structure relationships of the CEI are shown in Figure 6.1:

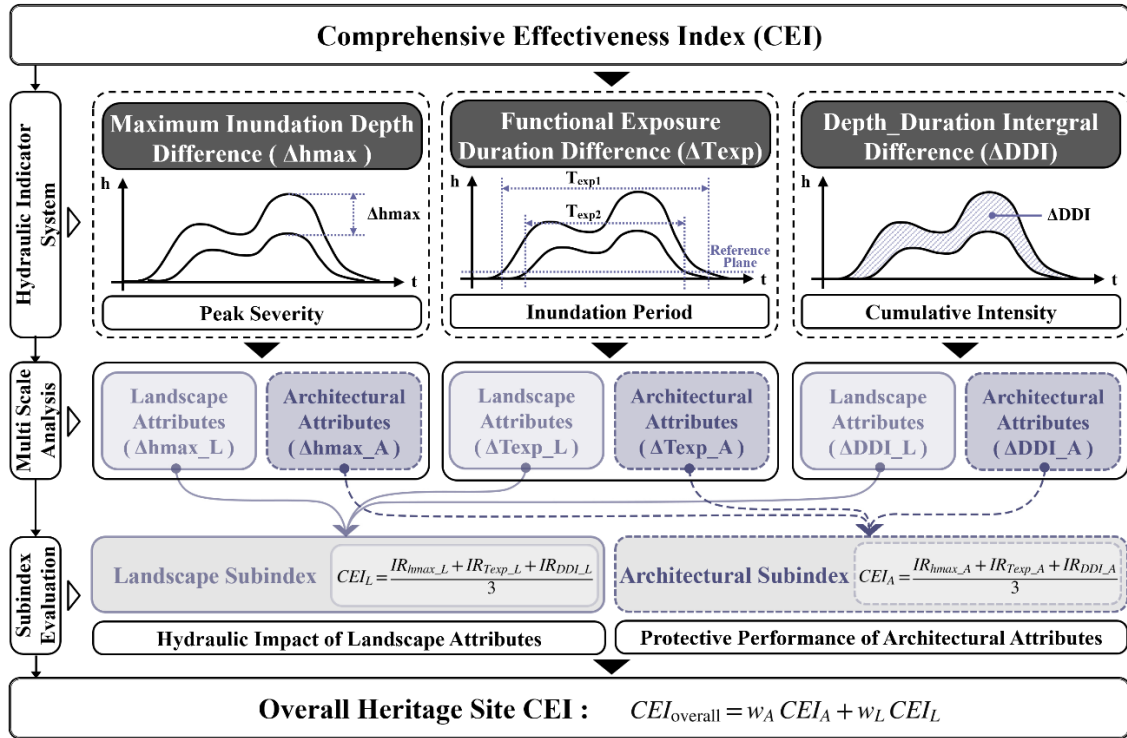


Figure 6.1 The framework of the Comprehensive Effectiveness Index (CEI).

6.1.2. Evaluation by landscape and building attributes

CEI is an evaluation framework encompassing both landscape and architectural attributes of heritage spaces, designed to distinguish and comprehensively understand the

impact effects of traditional resilience measures across different spatial levels. Cultural heritage conservation focuses not only on the structures themselves but also on their surrounding landscape environments and buffer zones, which equally bear significant conservation value (UNESCO, 2011). However, from a disaster resilience perspective, most flood control projects essentially redistribute risks spatially rather than eliminating them entirely (Mitomi et al., 2023). Therefore, to scientifically assess the dual impacts of a measure on cultural heritage, it is necessary to conduct a graded evaluation of the effects on both the protected object itself and its surrounding environment.

Within this research framework, heritage sites are first categorized into two levels: “building attributes” and “landscape attributes.” The building subindex measures the direct protective effect of conservation measures on the main heritage structures, while the landscape subindex comprehensively evaluates the impact of these measures on the surrounding landscape patterns and environmental carrying capacity. Combining these two subindexes brings a comprehensive CEI index for the heritage site as a whole, thereby establishing a quantifiable and balanced evaluation standard between enhancing the protection of the heritage entity and reducing environmental impacts.

6.1.3. Calculation methods and weighting scheme

The above core metrics are calculated based on the output data from the 2D extended model established in Chapters 4 and 5. To integrate the spatially distributed simulation results and obtain a single representative value for each indicator, the area-weighted method was applied using Eq. (20) to compute the average value (X) for each indicator.

$$X_m = \frac{\sum_i A_i \times k_{m,i}}{\sum_i A_i} \quad (20)$$

Here, X_m denotes the area-weighted value of indicator m ($h_{\max}$, $T_{\exp}$, DDI) within the area, A_i represents the area of mesh i and $k_{m,i}$ indicates the value of indicator m within mesh i . This calculation is performed separately for each indicator under scenario A and scenario B. Subsequently, the improvement rate (IR) relative to scenario B is calculated for each indicator, presenting the relative change in indicator values attributable to the presence of piloti in a dimensionless form. This calculation employs Eq. (21):

$$IR_m = \frac{X_m^{(2)} - X_m^{(1)}}{X_m^{(2)}} \quad (21)$$

Among these, $X_m^{(1)}$ and $X_m^{(2)}$ represent the area-weighted indicator values under scenario A and scenario B, respectively. A positive result indicates a beneficial reduction in flood impact, while a negative result signifies an adverse effect. Based on the improvement rates calculated for each indicator, composite calculations can further provide subindexes for landscape and building attributes. This section assigns equal weights to each indicator's improvement rate, aiming to equally aggregate three dimensions of peak severity, duration impact, and cumulative intensity. The calculation formulas are given by Eq. (22) and Eq. (23):

Landscape Subindex:

$$CEI_L = \frac{IR_{h_{max},L} + IR_{DDI,L} + IR_{T_{exp},L}}{3} \quad (22)$$

Architectural Subindex:

$$CEI_A = \frac{IR_{h_{max},A} + IR_{DDI,A} + IR_{T_{exp},A}}{3} \quad (23)$$

Among these, CEI_L represents the landscape subindex, while CEI_A denotes the architectural subindex. Ultimately, the comprehensive effectiveness index for heritage sites is derived through a weighted average of landscape and architectural subindex, serving to evaluate the overall impact of flood control measures on heritage sites. Its calculation is shown in Eq. (24). The calculation results range from -1 to 1, where positive values indicate that the countermeasure has a positive effect on flood reduction at the heritage site, while negative values indicate a negative effect. The value of the absolute number is directly proportional to the intensity of the impact.

$$CEI_{overall} = w_L \times CEI_L + w_A \times CEI_A \quad (24)$$

In the formula, w_L and w_A are the weight coefficients for the landscape and architectural subindexes, respectively. This means that $w_L + w_A = 1$. Weight assignments are determined by the relative importance of landscape and architectural elements within the site's conservation objectives, such as the heritage designation level (Arrighi et al., 2023), the relative contribution rate to Outstanding Universal Value (OUV) and its key attributes (UNESCO et al., 2022), site scale, or restoration costs.

CEI is an evaluation system that quantitatively assesses the effectiveness of traditional flood mitigation measures from a flood hazard perspective. It should be noted separately that subsequent simulation results indicate relatively low overall flow velocities across the study area. The primary impacts of flooding are due to short-term hydrostatic pressure or buoyancy, as well as long-term non-physical effects. Additionally, the influence of lower velocities can be indirectly assessed through variables related to water depth (Kelman and Spence, 2004). Therefore, velocity is not included as an evaluation indicator in the existing assessment framework. However, for different heritage sites affected by flooding, if higher flow velocities significantly increase dynamic water pressure, some velocity indicators must be added to supplement the evaluation system (Kreibich et al., 2009).

6.2. Evaluation of traditional flood mitigation measures

The impact of traditional passive measures on flood risks at heritage sites in contemporary environments will be examined using Katsura Imperial Villa as a case study, including the flood dynamics of flood mitigation effects and quantitative evaluation. Katsura Imperial Villa has long been regarded as a prototype of Japanese garden design (Imperial Household Agency) and a historical example of “modernity” in Japanese architecture by architectural masters such as Bruno Taut, Walter Gropius, and Le Corbusier (Ishimoto and Tange, 1972). Therefore, when selecting weights for the CEI calculation, the subindex weight coefficient for the Katsura Imperial Villa case is set to 1:1, reflecting the equal emphasis on architectural and landscape attributes within this heritage site.

6.2.1. CEI calculation and analysis of piloti

The data for evaluating the flood mitigation effects of the piloti structure were derived from simulations conducted using the 2D extended hydrodynamic model under two scenarios. Scenario A represents the actual existing condition, featuring a stilted ground floor where the building footprint is permeable to flow; Scenario B serves as the control virtual scenario, assuming an at-grade ground floor where the footprint is

impermeable as a solid obstacle. The spatial distribution of hydraulic indicators shown in Figs. 6.2a, 6.2b, and 6.2c indicates that positive values represent an increase due to the presence of piloti, while negative values denote a reduction. A comparative analysis reveals clear spatial differentiation of the three CEI indicators ($\Delta h_{\max}$, ΔT_{exp} , ΔDDI) at both architectural and landscape levels: (i) Regarding maximum inundation depth difference, piloti significantly reduces peak values in the architectural section, while the upper part of the landscape area shows a slight increase and the downstream portion experiences a minor decrease (Fig. 6.2a); (ii) In terms of functional exposure duration difference, the existing piloti elevate the habitable floor of the structure, significantly reducing the inundation period, whereas the landscape areas exhibit minimal overall change (Fig. 6.2b); (iii) Concerning the depth-duration integral difference, the use of piloti greatly mitigates cumulative hazards for buildings. Areas near the buildings show a slight decline, while the landscape region experiences a slight overall increase, with the upstream section showing a slightly higher rise compared to the downstream area (Fig. 6.2c). The CEI evaluation results further confirm the discussion on the flood mitigation mechanism of the piloti structure in Section 4.3.3. $\Delta h_{\max}$ indicates (Fig. 6.2a) that while water depth decreases within the building area, the surrounding environment exhibits a slight increase upstream and a slight decrease downstream. The indicators ΔT_{exp} (Fig. 6.2b) and ΔDDI (Fig. 6.2c) also show similar spatial divergence effects. The direct cause is that piloti reduce the effective flood storage capacity within the building footprint, leading to a slight increase in flood volume in the upstream environment where the building occupies a large area due to the principle of volume conservation.

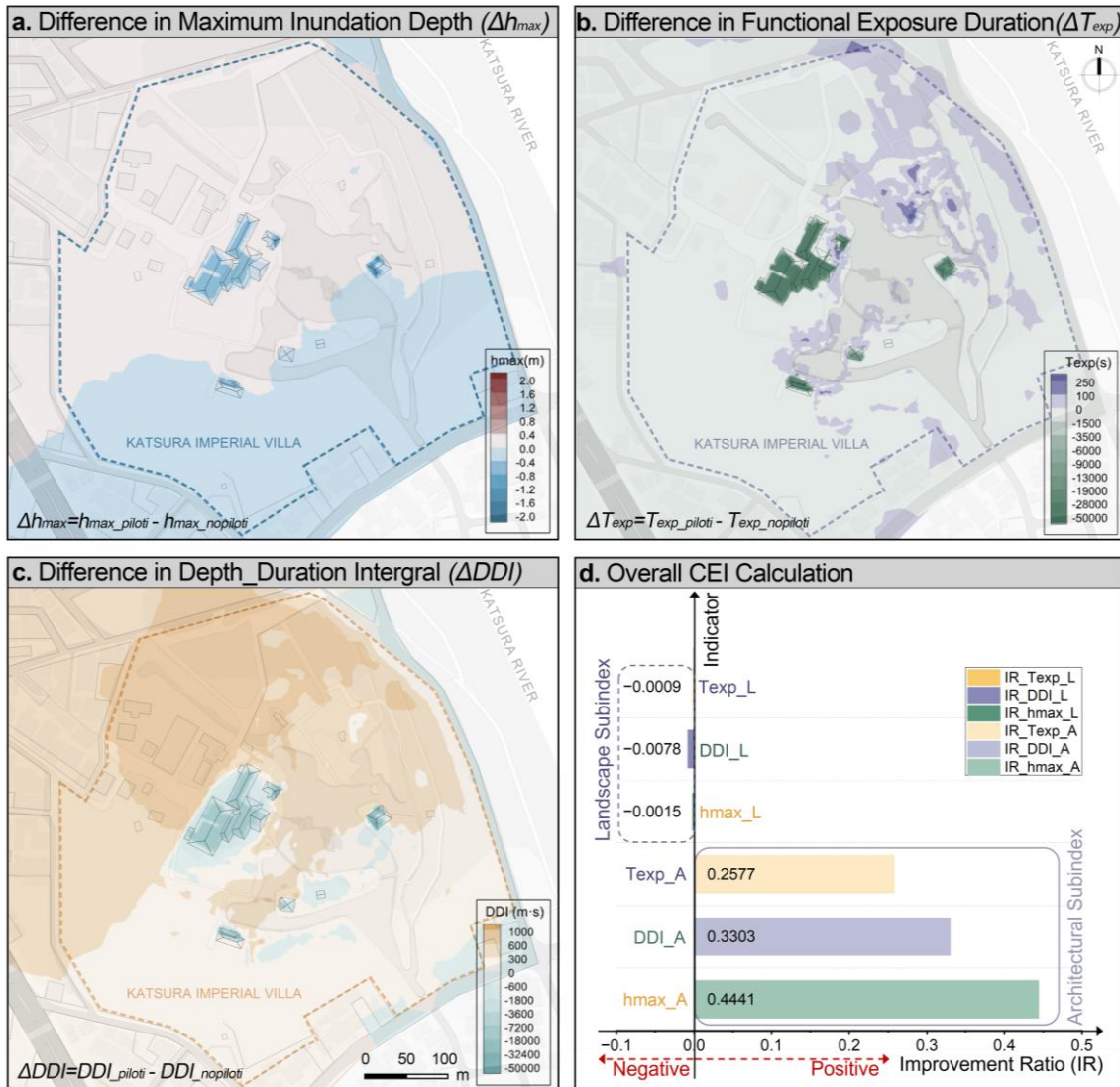


Figure 6.2 Spatial distribution of indicators for piloti: (a) maximum inundation depth difference; (b) functional exposure duration difference; (c) depth_duration intergral difference; (d) overall CEI calculation result.

Following spatial variance analysis, the Comprehensive Effectiveness Index (CEI) was calculated (Fig. 6.2d). First, for each of the two simulation scenarios, the average value (X) of the three indicators was calculated separately based on the two subindex levels (architecture and landscape), weighted by the area of the computational mesh in the numerical simulation. Then, the improvement rate (IR) for this indicator factor was calculated for both scenarios. The subindex was obtained as the arithmetic mean of the three improvement rate values. Finally, combining the two subindexes produces the

overall CEI for the heritage site. Results indicate: (i) The CEI for the architectural area is 0.344, indicating that piloti significantly reduces flooding in this area. All three indicators (maximum water depth, exposure duration, and water depth time integral) show positive values, with the most pronounced mitigation observed for maximum water depth. The average improvement across all three indicators exceeds 30%; (ii) The CEI for the landscape area is -0.003, indicating piloti have a very slight negative effect on flood reduction in this area, with minimal adverse impacts across all three indicators. This can be attributed to both the mechanism of action and spatial distribution. On one hand, the effective water storage capacity within buildings is primarily contained within the elevated space within the building footprint, limiting the amount of water overflowing into the landscape environment. On the other hand, piloti structures occupy a relatively small proportion of the site area, weakening their hydrological redistribution effects. (iii) For the heritage zone, where both built and landscape elements are equally important, the composite CEI of 0.170 indicates that piloti structures moderately reduce flood impact intensity across the entire heritage area, with this mitigation having practical significance. Detailed numerical results for each component are presented in Table 6.1.

Table 6.1 Stepwise results for CEI calculation of piloti.

Landscape Attributes				Architectural Attributes			
	X_m	IR_m	CEI_m		X_m	IR_m	CEI_m
$X_{hmax}(m)$	X_{hmax}^1	1.443		$X_{hmax}(m)$	X_{hmax}^1	0.790	
	X_{hmax}^2	1.441	-0.001		X_{hmax}^2	1.420	0.444
$X_{Texp}(s)$	X_{Texp}^1	41407		$X_{Texp}(s)$	X_{Texp}^1	27307	
	X_{Texp}^2	41371	-0.001		X_{Texp}^2	36789	0.258
$X_{DDI}(m \cdot s)$	X_{DDI}^1	42332		$X_{DDI}(m \cdot s)$	X_{DDI}^1	25537	
	X_{DDI}^2	42004	-0.008		X_{DDI}^2	38133	0.330
CEI_{overall}				0.170			

6.2.2. CEI calculation and analysis of porous fence

The CEI evaluation of the porous fence is also based on a comparison of two scenarios derived from the extended 2D hydrodynamic model: Scenario A represents the existing condition with all porous fences in place, while Scenario B serves as a virtual reference scenario with the fences removed. Figures 6.3a, 6.3b, and 6.3c illustrate the

distribution of differences in three hydraulic indicators for the Katsura Imperial Villa heritage area (measured relative to the fence scenario versus the no-fence scenario; positive or negative values indicate an increase or decrease in the indicator under the existing fence scenario). Spatially, the porous fence exhibits a slight negative impact on all three indicators within the heritage area, with locally pronounced positive effects concentrated on the downstream side of the southern fence and the downstream side of the eastern fence. Regarding Δh_{max} (Fig. 6.3a), the global water depth within the Katsura Imperial Villa (upstream of the fence) shows a slight increase, clearly corroborating the phenomenon of upstream water accumulation caused by the fence, as mentioned in subsections 5.1.3 and 5.4.3. The peak water depths downstream of the eastern and southern fences showed slight decreases, with the southern decrease being more pronounced due to the solid fence forming complete water blockage and the lower terrain elevation. Correspondingly, the spatial distribution of ΔT_{exp} and DDI differences also exhibited simultaneous changes (Fig. 6.3b, 6.3c), reflecting enhanced exposure duration and depth_duration integral caused by upstream retention. Overall, the flood attenuation effect of the porous fence can be objectively summarized as follows: the existing fence in this case exhibits a slight negative impact, primarily reflected in minor adverse changes to various indicators due to upstream water retention caused by the fence.

The quantitative CEI results (Table 6.2) further confirm that this negative effect exhibits consistent secondary impacts across both subindexes, though the magnitude is small. Key comparative findings include: (i) The CEI values for the built area and landscape area are -0.015 and -0.014, respectively, indicating that the porous fence under the existing layout slightly increases flood risk across the entire area; (ii) All three indicators (maximum water depth, exposure duration, and water depth time integral) exhibit negative values across both subindexes, indicating a uniform negative impact on each indicator. The most notable adverse effect is on maximum water depth, while the impact on exposure duration is minimal. This suggests the fence primarily influences localized flood redistribution rather than significantly altering overall duration; (iii) The composite CEI of -0.015 indicates that, from the perspective of the heritage area, the spatial layout of existing fences is not conducive to mitigating flood impact intensity.

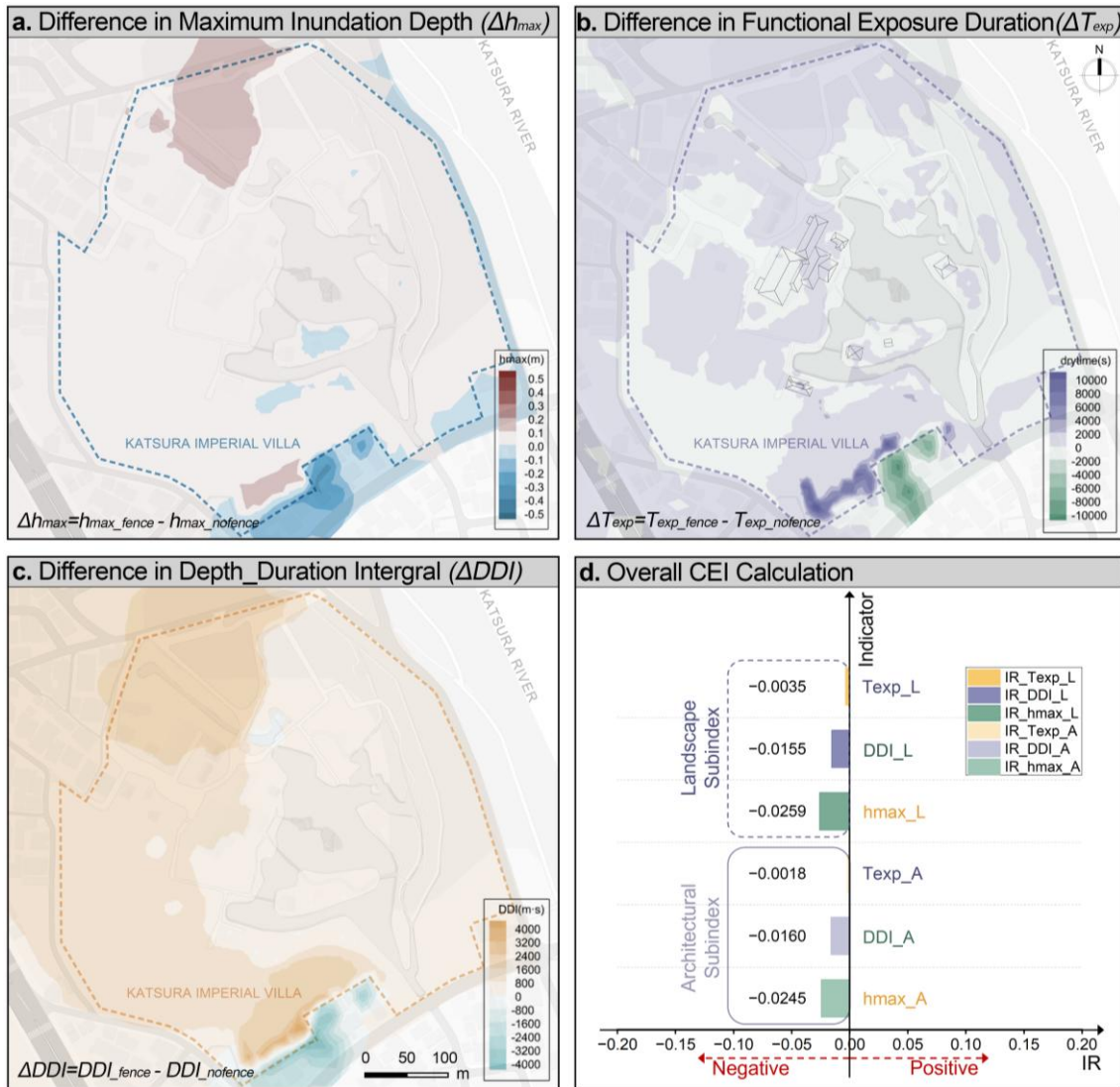


Figure 6.3 Spatial distribution of indicators for porous fence: (a) maximum inundation depth difference; (b) functional exposure duration difference; (c) depth_duration intergral difference; (d) overall CEI calculation result.

The main reason is that the existing fences were logically positioned to address lateral inflows from the Katsura River, hence their primary arrangement along the riverbank. However, under current topography and hydrological conditions, the dominant flood inflow direction has shifted to the northwest, causing a mismatch between fence orientation and flow direction. This locally produces a slight flood reservoir effect. This finding also suggests that porous fence designs must carefully consider both upstream and downstream conditions, particularly avoiding severe adverse impacts on upstream areas within floodplains.

Table 6.2 Stepwise results of CEI calculation for porous fence.

Landscape Attributes				Architectural Attributes					
		X _m	IR _m	CEI _m			X _m	IR _m	CEI _m
X _{hmax} (m)	X _{hmax} ¹	1.644			X _{hmax} (m)	X _{hmax} ¹	1.631		
	X _{hmax} ²	1.602	-0.026			X _{hmax} ²	1.592	-0.025	
X _{Texp} (s)	X _{Texp} ¹	40748			X _{Texp} (s)	X _{Texp} ¹	45021		
	X _{Texp} ²	40607	-0.003			X _{Texp} ²	44941	-0.002	
X _{DDI} (m·s)	X _{DDI} ¹	47821			X _{DDI} (m·s)	X _{DDI} ¹	43789		
	X _{DDI} ²	47090	-0.016	-0.015		X _{DDI} ²	43098	-0.016	-0.014
CEI _{overall}				-0.015					

6.2.3. Comparison analysis between different countermeasures

This section compares the spatial distribution and quantification of flood mitigation effects at the heritage site in the current environment, focusing on two types of traditional passive measures preserved at Katsura Imperial Villa. The primary effect of piloti demonstrates direct disaster mitigation for the building structure. CEI results indicate that piloti exhibit a composite positive effectiveness of 0.170 at Katsura Imperial Villa, with architectural and landscape subindexes of 0.344 and -0.003 respectively. This suggests piloti significantly protect the main structure while exerting a slight negative impact on the surrounding landscape. Their fundamental mechanism involves altering local flood behavior through newly created flow channels beneath the structure and the elevation of functional layers. Concurrently, due to the limited footprint of the structure, the negative effect on the landscape layer is weak.

The primary effect of the porous fence is that its negative impacts outweigh its positive benefits. CEI results indicate that the porous fence at Katsura Imperial Villa exhibits a combined negative effectiveness of -0.015. This suggests that under current environmental conditions, the spatial layout of the existing fence slightly negatively impacts flood safety at the heritage site. The direct cause lies in the mismatch between the fence's orientation and the prevailing flood flow direction, positioning Katsura Imperial Villa become upstream part of the fence and causing minor floodwater retention on the site. As a passive measure for future application, while porous fences (particularly bamboo-woven fences with specific thickness and porosity) may possess potential for

filtering sediment and floating debris and reducing inflow intensity (Kawasaki et al., 2013), they are more suitable as fine-tuning measures requiring careful design. Particular emphasis should be placed on systematically evaluating and balancing the potential benefits of the fence for downstream areas against the significant negative impacts it may cause to the upstream environment.

Overall, both approaches redistribute floodwater between structures and landscapes, or between upstream and downstream areas, by altering local flow conditions. This phenomenon aligns with the risk redistribution patterns commonly observed in engineering flood mitigation measures (Mitomi et al., 2023). *Piloti* offer a more direct flood reduction effect and provide more significant building protection. However, for existing cultural heritage sites, *piloti* constitute spatial modification measures that are often difficult to implement without altering the authenticity and integrity of the heritage. Therefore, their primary significance is to provide resilience insights for future new construction or renewal designs. In contrast, porous fences rely heavily on specific layouts and upstream-downstream relationships. If misaligned with the primary flood flow direction, they may heighten the adverse effects of upstream disaster impacts. Consequently, their application requires careful assessment.

6.3. Potential of rain gardens for resilience optimization

Rain gardens represent a prototype within green infrastructure systems that integrate hydrological regulation with landscape design. By enhancing site infiltration capacity and water storage space, they effectively reduce peak flood flows, decrease total runoff volume, and improve water quality (Jia et al., 2016; Sharma and Malaviya, 2021; Zhang et al., 2020), while enhancing the visual aesthetics and ecological quality of landscape spaces. Notably, rain gardens lack rigid form or size restrictions, demonstrating exceptional adaptability to diverse environments within high-density urban areas. For cultural heritage sites and their surrounding environments, rain gardens exhibit significant potential as an intervention-based flood mitigation measure. Their low-impact and reversible characteristics allow integration into existing heritage settings without requiring extensive gray infrastructure modifications. Therefore, this section explores

rain gardens as a potential intervention for enhancing flood resilience in heritage sites. Based on prototype field experiments, we conduct quantitative assessments and numerical modeling of rain garden hydrological performance to establish a research foundation for subsequent practical applications.

In Kyoto, Japan, research on rain gardens has been further linked to traditional garden practices. The garden at Shōkoku-ji Temple in Kyoto served as a field experiment site for a traditional-style rain garden (Yamashita et al., 2023). Results demonstrated that without altering its historical layout, the garden effectively captured and infiltrated significant roof runoff through topographical depressions, gravel layers, and vegetation arrangements. This design produced virtually no external overflow during small to moderate rainstorms. This demonstrates that Japanese traditional gardens incorporate stormwater management functions beneath their formal aesthetics, highlighting the immense potential of rain gardens in enhancing flood resilience for cultural heritage sites.

6.3.1. Basic information

The target rain garden for this study is located south of the main building at the Uji River Open Laboratory of Kyoto University's Disaster Prevention Research Institute, covering a total area of approximately 26m². In terms of hydrological conditions, the rain garden primarily receives runoff from building roofs, surrounding ground surfaces, and direct rainfall. Roof runoff is conveyed to the ground via downspouts on the east and west sides. Half of the runoff from the west downspout is directed into the rain garden's surface, while the other half enters the west well. This water then flows through underground pipes into the rain garden's pond for temporary storage. Half of the runoff from the east downspout enters the pond directly, while the other half enters the east well and is subsequently discharged into the urban stormwater drainage system (Fig. 6.4).

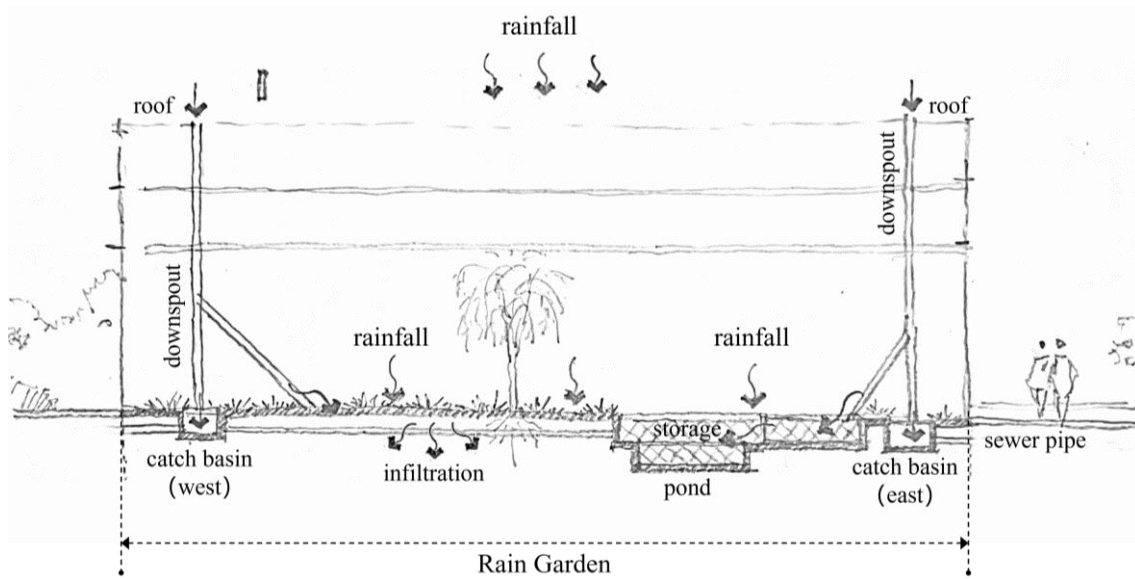


Figure 6.4 Conceptual design of rain garden

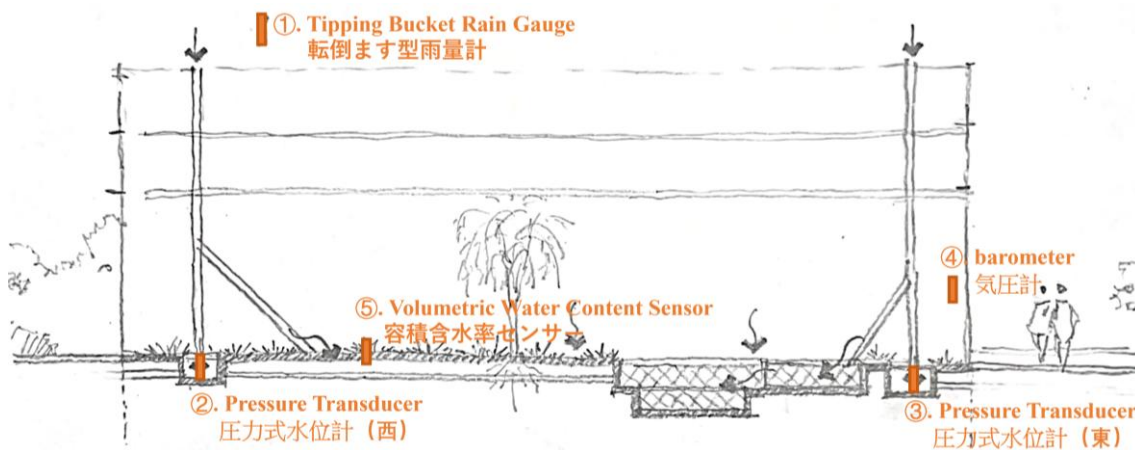


Figure 6.5 Layout of monitoring instruments

To conduct a quantitative study of the stormwater retention capacity of this rain garden, monitoring equipment was installed on-site. This included a tipping bucket rain gauge on the roof, pressure-type water level gauges in the well on the east and west sides, volumetric moisture content sensors in the four soil layers of the rain garden, and a pressure gauge. These devices continuously record key process data such as rainfall, storage depth, and soil moisture content (Fig. 6.5). These observations will be utilized in Section 6.3.3 for model parameter calibration and validation. The total catchment area of the rain garden comprises two components: one from the roof (249 m²) and another from the garden itself (19.5 m²) (Fig. 6.6).

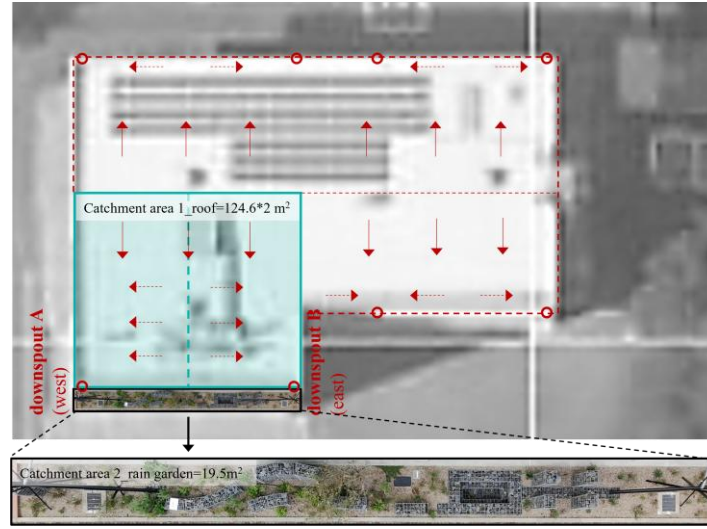


Figure 6.6 Catchment area

6.3.2. Basic data analysis of rain garden

1) Rainfall–well water level dynamics.

This part compares the rainfall data with the water level in the wells on the east and west sides. The tipping-bucket rain gauge used in this experiment outputs a time series of bucket tipping events, with each tipping corresponding to 0.2 mm of rainfall. This study aggregated the raw tipping bucket records into the number of tipping events n_t per Δt time step (10 min), calculating the rainfall amount for that time step as $P_t = n_t \times 0.2 \text{ mm}$ (Fig. 6.7). Further division by Δt calculates the average rainfall intensity, which will serve as the upper rainfall boundary condition for the model. The total monitoring period is from 2025/10/16 to 2026/01/26. No overflow occurred throughout the entire monitoring interval.

During the monitoring period, rainfall events occurred more frequently from October to November, while rainfall decreased markedly from late December onward (Fig. 6.7). Overall, both wells responded rapidly to rainfall, with water depths rising almost simultaneously, indicating a short transport time from roof runoff to the well system. The west well exhibited smoother and more gradual water-level fluctuations, whereas the east well showed larger variations and repeatedly dropped to zero during winter. This difference is likely attributable to the east well's connection to the urban sewer network, which provides greater drainage capacity.

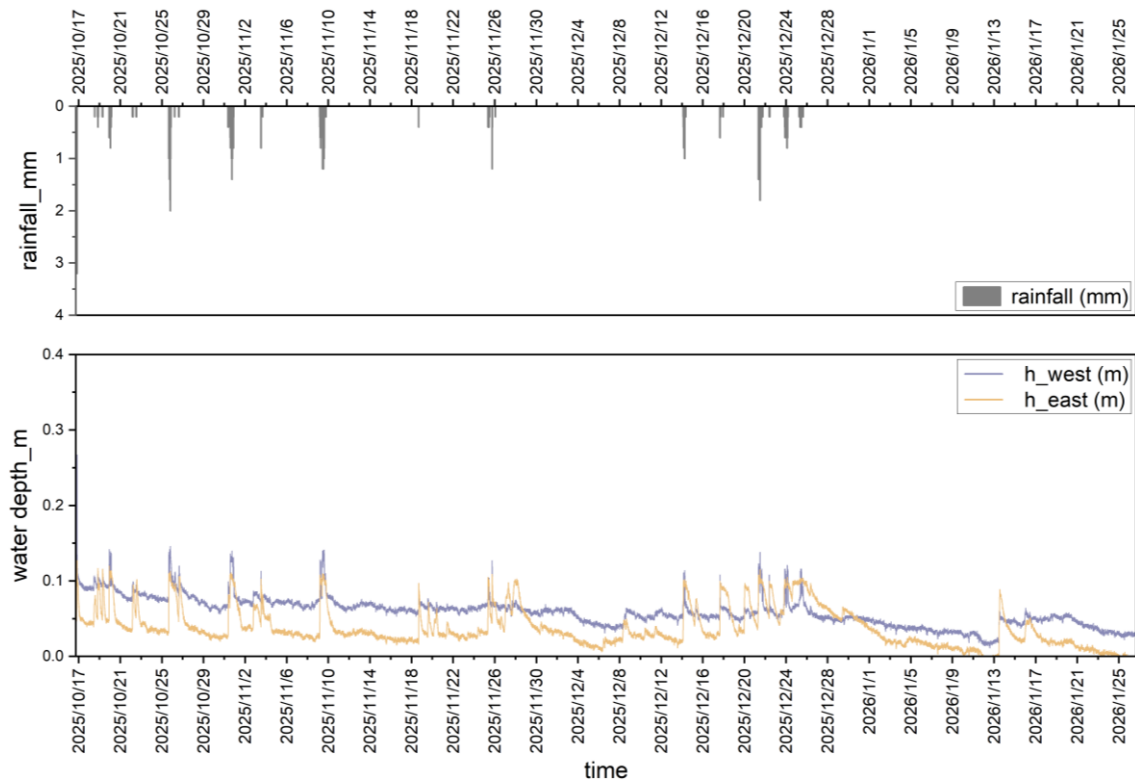


Figure 6.7 Rainfall and water depth in the west and east wells (2025/10/16–2026/01/26)

2) Soil moisture content statistics.

During the continuous monitoring period (2025/08/19–2026/01/26), the volumetric soil moisture at four depths (10, 20, 35, and 50 cm) showed a clear pulse-like response to rainfall (Fig. 6.8). After rainfall, soil moisture increased quickly, followed by a slow recession lasting from several hours to tens of hours. The rise magnitude and recession duration varied across events. During dry periods, soil moisture gradually decreased and became relatively stable. In general, the deeper layer (especially 50 cm) showed smoother and slower decay, while the shallow layers (10–20 cm) more often showed sharp peaks and higher-frequency fluctuations. This pattern reflects the basic soil-water process in the rain garden: rainfall provides infiltration input, and then soil moisture decreases due to internal redistribution (gravity drainage and lateral spreading) and evapotranspiration. Seasonal conditions and soil hydraulic properties can also change the recession speed and duration.

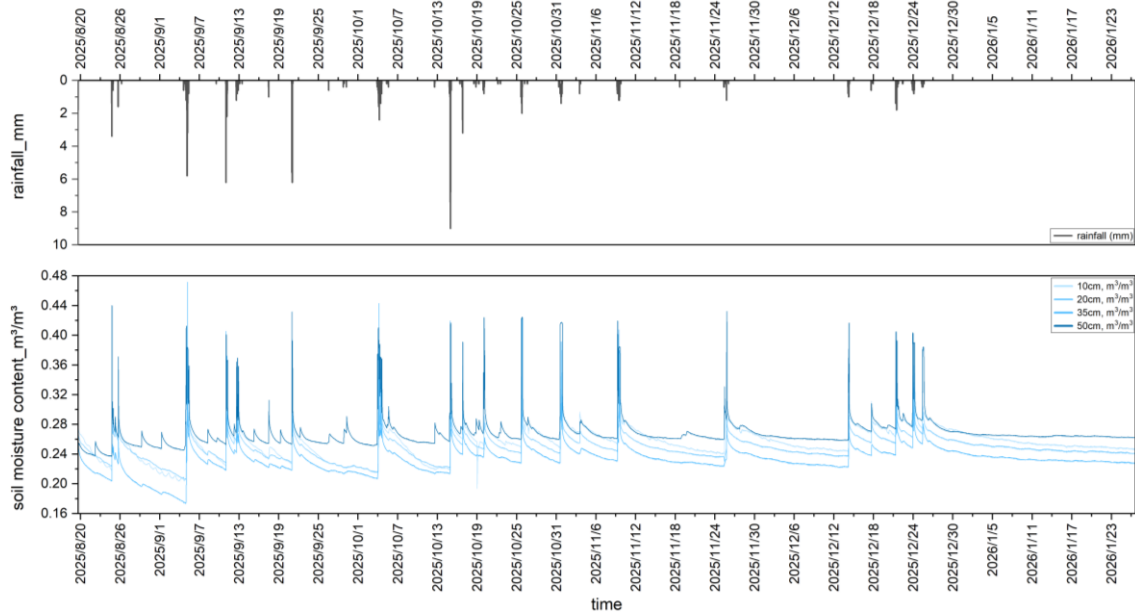


Figure 6.8 the volumetric soil moisture at four depths (10, 20, 35, and 50 cm)

By zooming in on typical events, two response patterns can be identified. In Pattern 1, rainfall often starts as light but lasts for some time (Fig. 6.9). In these events, the 50 cm sensor responds earlier than the 10/20/35 cm sensors: moisture at 50 cm increases first and quickly reaches a high level, sometimes forming a plateau. The shallow layers rise later and often show sharper peaks. This order is different from the common top to down infiltration expectation. It might suggest that, in these kinds of events, the moisture supply near the sensors is not mainly controlled by vertical infiltration from the ground surface. Instead, it may be driven by a deeper or lateral supply. Considering the local drainage layout, a reasonable explanation is that early rainfall can already provide a continuous subsurface input through the storage and underground flow path, even when no surface ponding is observed. This subsurface water can spread laterally in soil and reach the area around the 50 cm sensor earlier, leading to the first response of deep layer. In addition, deeper soil is less affected by evapotranspiration, which can also make the 50 cm curve smoother and more stable.

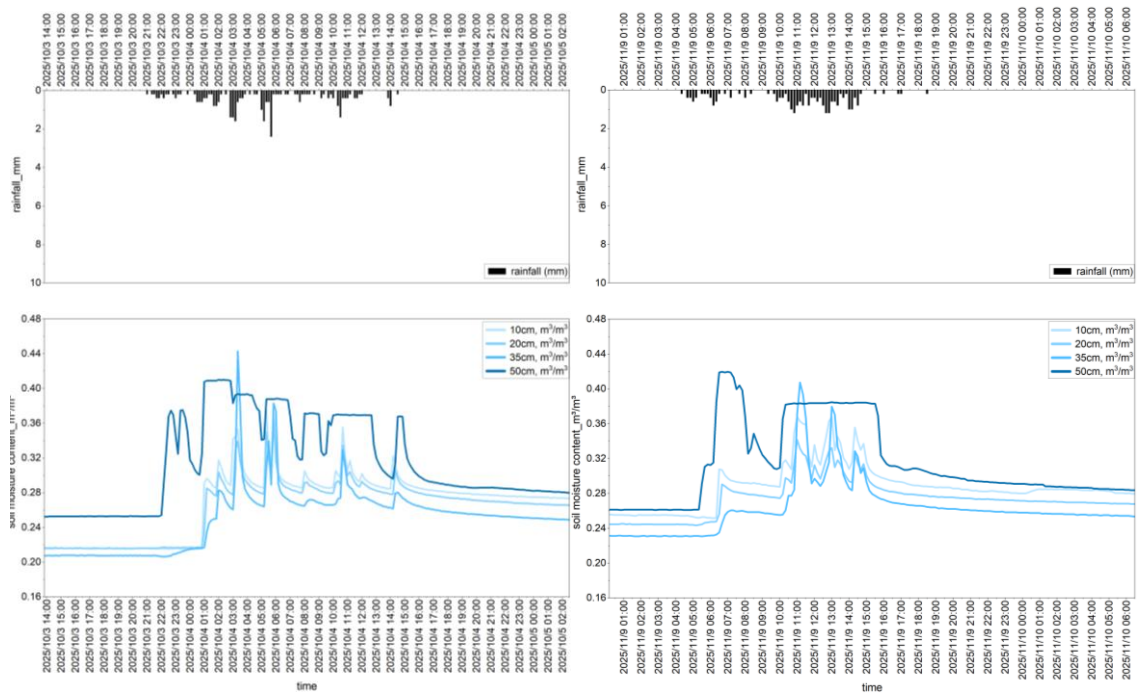


Figure 6.9 Pattern 1. the deeper sensor responds earlier

In Pattern 2, rainfall is short but intense at the beginning (Fig. 6.10). In these events, soil moisture typically increases from shallow to deep: 10 cm rises first and fastest, 20 cm and 35 cm follow, and 50 cm increases last, sometimes only slightly. This is consistent with the classical wetting-front process in vertical infiltration: rainwater first enters the shallow soil, and then the wetting front moves downward under gravity, causing a delayed response in deeper layers. Therefore, 50 cm becomes the slowest layer.

In summary, when rainfall includes an early period of light but continuous input, a continuous subsurface supply and lateral spreading may become important, and the 50 cm sensor can respond first. In contrast, when rainfall starts with a strong beginning, vertical infiltration near the surface dominates, and the response order returns to 10 cm first, and 50 cm last. In the observation period of this study, the pattern of 50cm first increase was frequently observed when rainfall began with a light but lasting stage, suggesting that the rain garden may have a subsurface lateral pathway that can dominate soil moisture changes in some events.

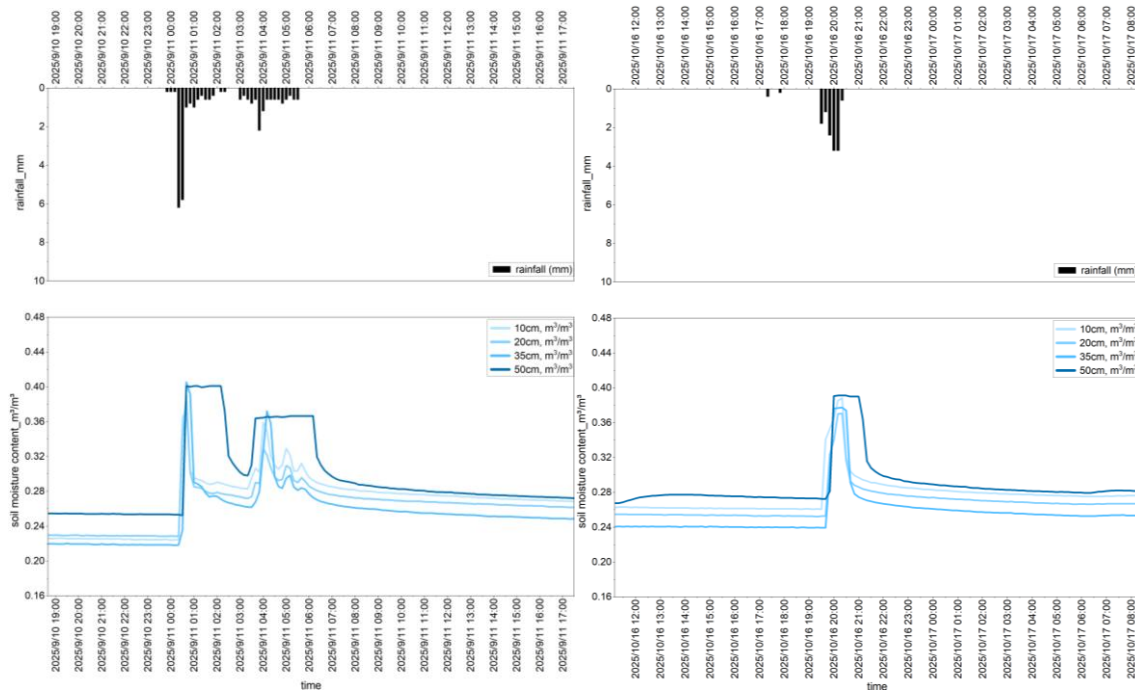


Figure 6.10 Pattern 2. the shallow sensor responds earlier

6.3.3. Future work: simplified infiltration parameterization of rain gardens

In future work, the rain garden can be treated as a functional unit with surface storage and infiltration capacity, and represented in a simplified way within a 2D inundation model. Practically, this can be done by adding an infiltration sink term only on the grid cells covered by the rain garden in the 2D shallow-water equations, so that its runoff reduction and delay effects can be captured. For the infiltration formulation, a practical first option is the Horton model, which describes infiltration capacity decreasing with time and requires only a small number of parameters. With the existing dataset (rainfall, soil moisture at four depths, and well water levels), a few representative events can be used for calibration and other events for basic checks, focusing on whether the inferred infiltration magnitude and the trend from fast to slow are reasonable. In addition, soil moisture at 10/20/35/50 cm can be combined into a profile-averaged wetness index (a thickness-weighted mean) to represent the initial soil wetness at the beginning of each event, and the initial and final Horton infiltration capacities can be allowed to change with

this wetness in a simple way. This approach avoids complex soil parameters and helps apply the rain-garden unit to scenario comparisons in other urban settings.

It is also important to note that no surface ponding or overflow was observed during the monitoring period, suggesting that under the current experimental configuration, the system can absorb inflow and provide flood mitigation under typical rainfall events in Kyoto. Therefore, this low-impact and flexible measure shows strong potential for flood resilience enhancement in cultural heritage sites, offering additional protection without major disturbance to heritage assets.

6.4. Flood optimization design in heritage sites

This section expands upon the understanding of traditional passive flood mitigation measures through CEI, proposing flood resilience enhancement strategies for heritage sites from the perspective of optimized flood reduction design. As traditional Nature-Based Solutions (NbS) and passive resilience strategies, elevated piloti foundations and porous fence with limited delay and reduced flood peaks have long been applied as passive flood mitigation approaches in floodplain environments and cultural landscapes. Learning from traditional wisdom underscores the significance of harmonious coexistence with the local environment and the importance of sustainable spaces (Priavolou, 2025). By incorporating these passive flood-adaptive architectural designs into 2D hydrodynamic models and supplementing them with enhanced designs to address flood hazards under new conditions, this section aims to provide quantitative evidence for comprehensive optimization designs targeting cultural heritage.

6.4.1. Feasibility of porous fence as a resilient design for heritage

Prioritizing the authenticity and integrity of cultural heritage, the porous fence selected in this section represent solutions that minimally interfere with existing layouts while perfectly integrating with ecology and nature. It holds potential as rare low-intervention engineering measures for heritage sites, though simulation studies on different layout scenarios for heritage sites remain limited. In contrast, as a strategy altering the spatial form of building ground floors, piloti is difficult to directly apply to

existing heritage structures. Nevertheless, it holds significant potential for promotion in contemporary urban and architectural design addressing future floodplain environments.

Unlike solid levees that completely block water flow, porous fences demonstrated flood regulation effects in Chapter 5 through experiments: upstream water levels rise, while downstream levels show a slight decrease within a limited range and a delayed flood peak. Unlike rigid levees that attempt to completely block floodwater on the outer side, porous fences are designed to coexist with floods (Fig. 6.11). Experimental findings in Chapter 5 indicate that porous fences significantly raise upstream water levels while delaying peak arrival times downstream, with relatively limited overall water level changes downstream. This suggests porous fences do not eliminate floods but function as micro-adjustment tools, redistributing floodwater at the local scale. Based on this foundation, this section treats the porous fence as a resilient measure that minimally interferes with heritage patterns and integrates with garden landscapes. It explores how the porous fence optimizes flood processes at different layouts and scales for key buildings and spaces within heritage sites.

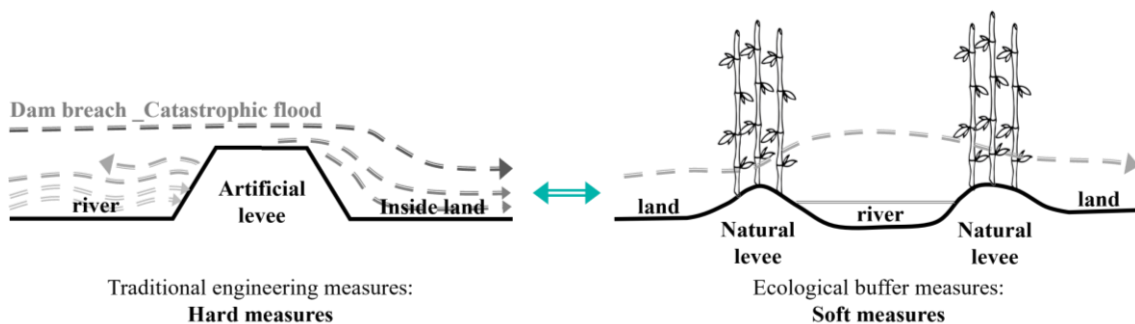


Figure 6.11 Different types of measures

6.4.2. Different layouts of porous walls

The study focused on the Katsura Imperial Villa case for porous fence renovation design. The renovation was based on two considerations: (i) The original porous fence was likely positioned alongside the Katsura River to address overflowing floodwater from the river under the original environmental conditions, with the fence facing the river. However, with increasing river management and embankment reinforcement projects, the more destructive floods in today's built environment originate from the upstream slopes

of the Katsura River (Fig. 6.12). The primary flood flow direction now enters the site from the northwest, requiring supplementary measures positioned to block the incoming flow; (ii) Many existing fences on the site either lack flood mitigation effectiveness due to excessive porosity or fail to integrate harmoniously with the natural environment and landscape aesthetics in terms of material and form (Fig. 6.13).

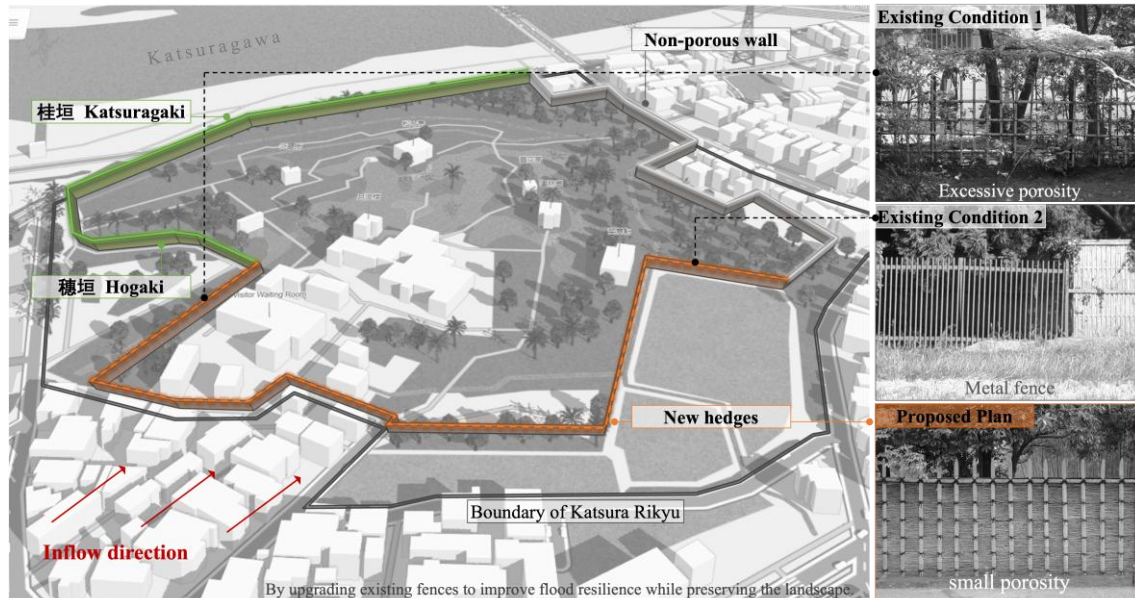


Figure 6.12 New inflow direction and undesirable existing fence

The optimization design will enhance flood protection and landscape aesthetics by retrofitting the undesirable existing fence. The modified fence will replicate the form of the original bamboo fence, with a porosity set at 0.1 to provide optimal flood protection. Figure 6.13 illustrates four optimized layout methods: Scenario A represents the current fence configuration, while Scenarios B–D add fences to the west (Plus 1), to the west and north (Plus 2), and to the west, north, and south to form an enclosed area (Plus 3).

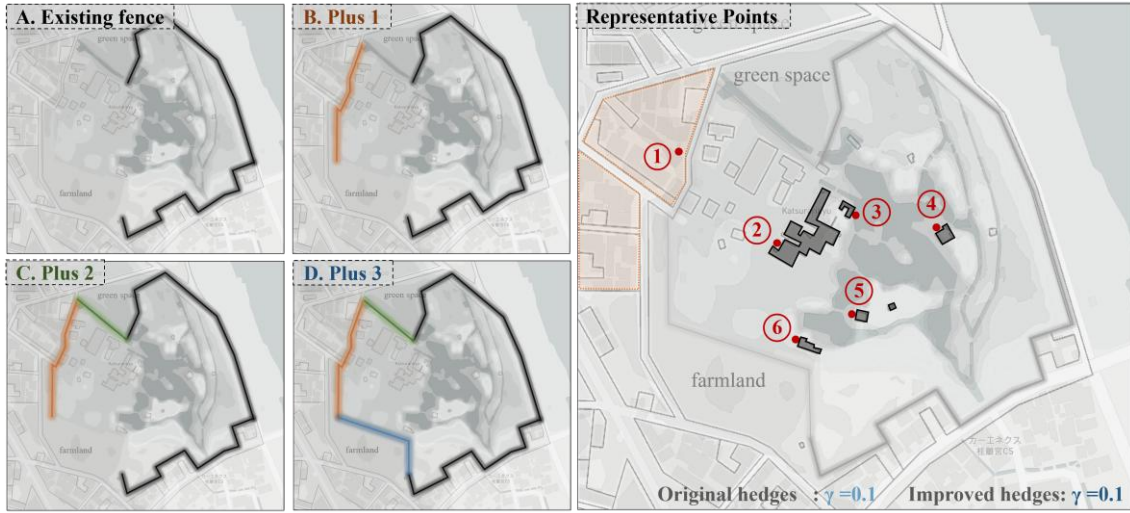


Figure 6.13 Four optimization design cases & six representative points

6.4.3. Comparison of flood mitigation effects

In order to compare the effects of different fence layouts on the inundation dynamics within the heritage site, this study selected six representative observation points: Point 1 is located upstream of the newly added fence to monitor the external environmental impact of the new measures. Points 2–6 are distributed around the core buildings (Fig. 6.14).

Figure 6.14 presents the water depth profiles at six representative points under four distinct scenarios. For the outer point 1, Scenario B (adding only a porous fence on the western side) significantly reduces peak water depth and markedly accelerates the receding process. This result appears inconsistent with the experimental finding in Chapter 5 that fences raise upstream water levels. However, it can be understood as a special case under specific site conditions. The western fence aligns roughly parallel to the primary inflow direction and has low porosity, functioning more like a flow-guiding boundary that rapidly directs water away from the local site, thereby reducing water depth. This case also suggests that in complex, real-world heritage spaces, the effects of porous fences are subject to the combined influence of multiple factors such as topography, inflow direction, and spatial layout. Consequently, practical applications must rely on numerical simulations tailored to specific contexts rather than simply applying idealized experimental conclusions.

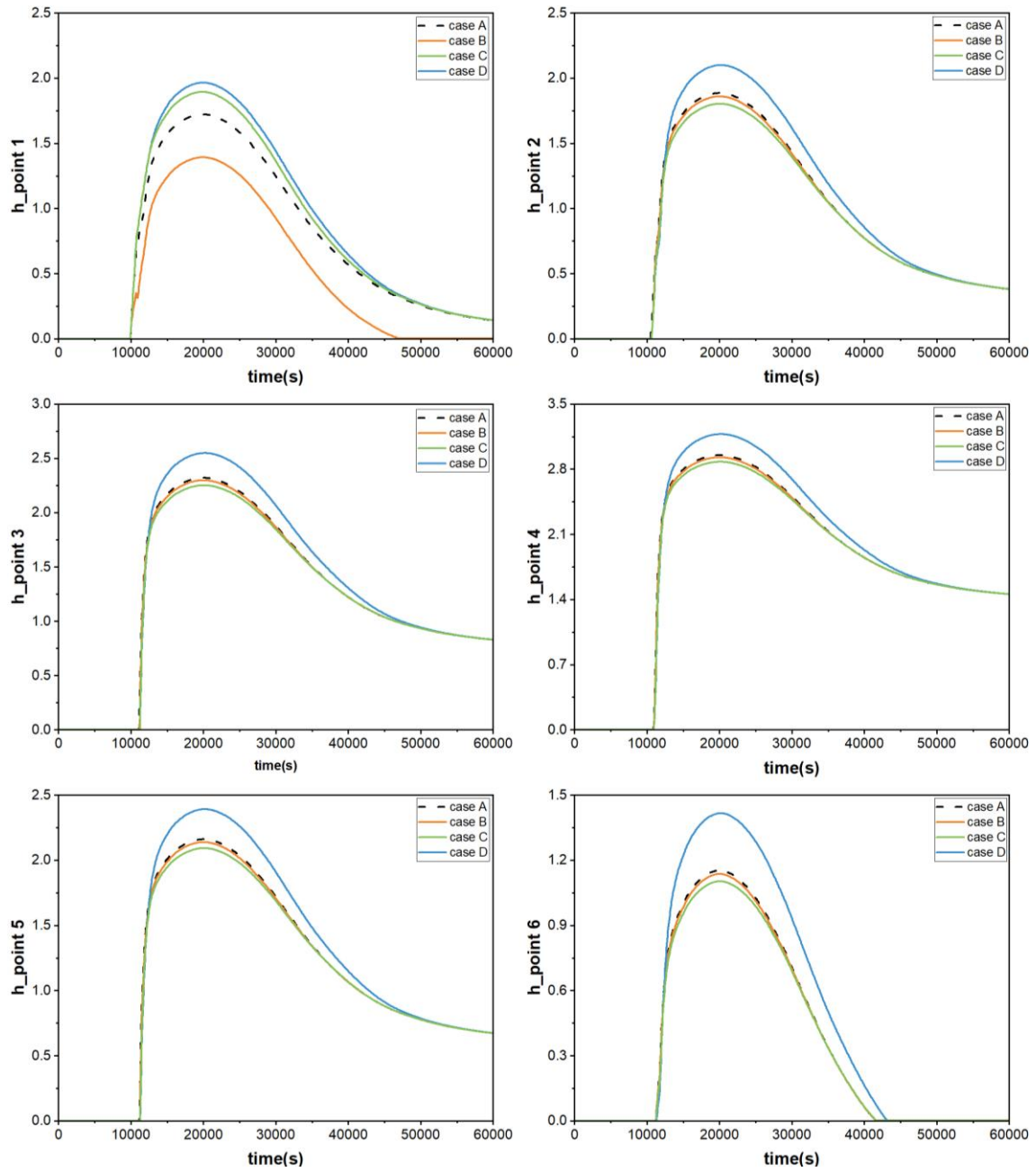


Figure 6.14 Different types of measures

For points 2 to 6 within the heritage site, these locations are all situated downstream of the newly added fencing and are designated as priority protection areas. As shown in Figure 6.14, Case C exhibits the most notable mitigation effect, with peak water depths at all points slightly lower than the current scenario. However, the difference is only approximately 0.05 m, and the flood peak arrival time shows only a very slight delay (around 600 seconds), without the significant delay observed in the experimental phenomenon. This is likely because the western and northern fences are positioned

directly against the primary inflow direction, creating some degree of flow obstruction. However, the fences' effect weakens progressively at greater distances from the structure. In contrast, Case D generally elevates peak water levels at these points and significantly delays the receding process, making it the least favorable arrangement. This suggests that enclosed structures may cause water retention, challenge the traditional perception that enclosed designs provide comprehensive protection.

Water depth contours further reveal the flow obstruction effects produced by walls with different spatial layouts (Fig. 6.15). The first column shows the initial inflow period ($t=10900s$), clearly indicating that flood spread occurs most rapidly in case A due to the absence of walls obstructing the incoming flow direction (Fig. 6.15a). During the sustained water level rise period ($t=15900s$), floodwater continuously enters Katsura Imperial Villa. The upstream fence additions in Cases C and D create upstream water retention outside the northern wall (green color), contrasting with Case A (Fig. 6.15b). This retains relatively more water within the area, particularly evident in the fully enclosed layout (Fig. 6.15h). During the flood discharge period following the peak, Case D exhibits significant obstruction of flood discharge due to the newly added southern fence (blue color) (Fig. 6.15i). This results in markedly increased water depth, expanded inundation area, and extended duration within the enclosed layout configuration.

Comparing the water depth-time curves from six representative points (Fig. 6.14) and analyzing the contour lines in the 2D water depth distribution (Fig. 6.15), it can be concluded that: Case C, featuring a barrier layout that intercepts inflow head-on while maintaining an opening downstream, offers the relatively optimal flood control effect among the existing alternatives. However, the improvement is extremely limited and comes at the cost of significantly increased water depth in the upstream area of the barrier. The surrounding area currently consists of residential zones, which cannot be considered regions with significant water storage capacity. Achieving a relatively balanced compromise of risks inside and outside the enclosure is challenging. Conversely, the fully enclosed layout shown in Scenario D significantly raises the peak water depth within the heritage site and extends the outflow duration. This approach should be avoided in actual flood prevention design.

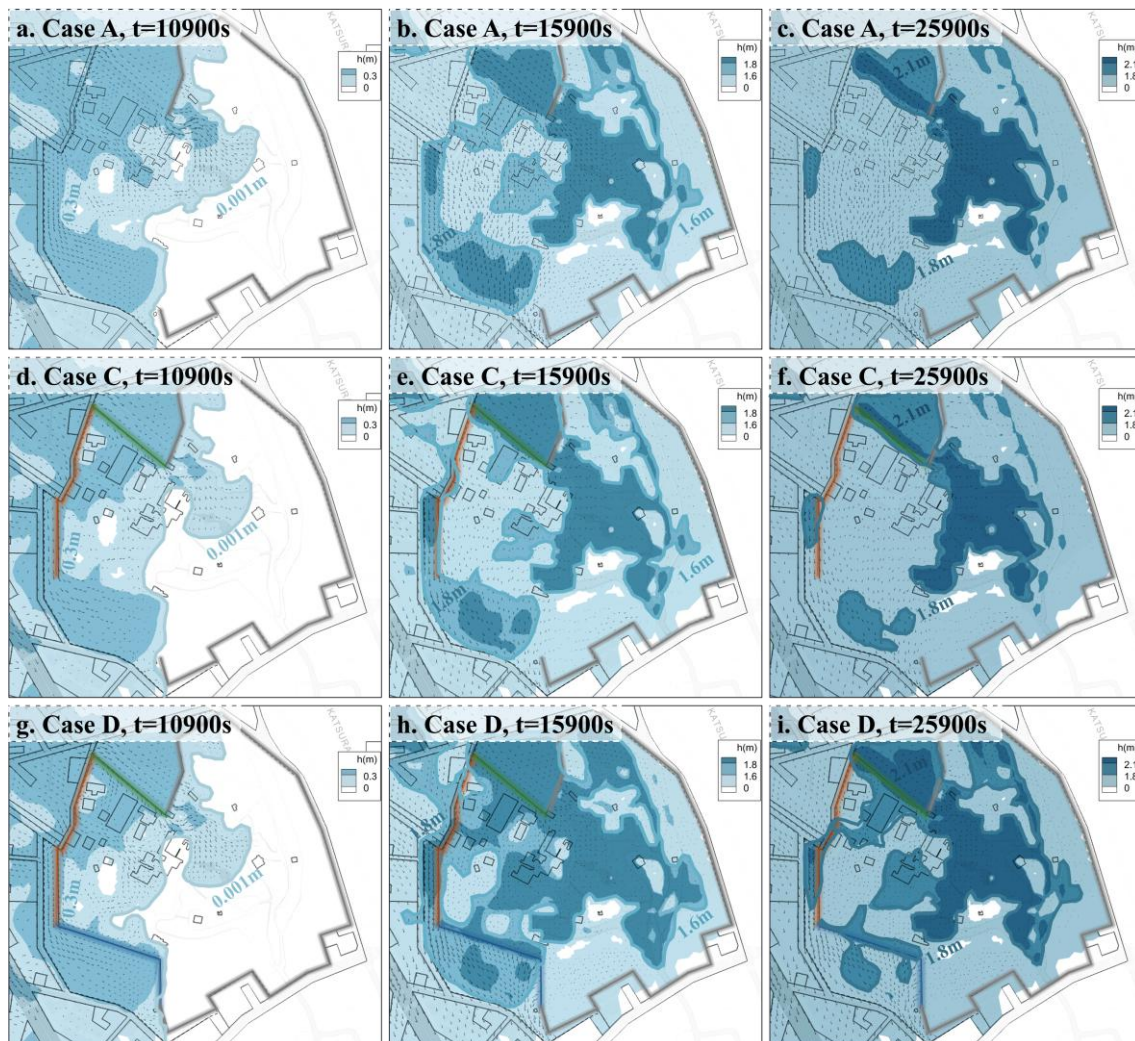


Figure 6.15 Water depth counter in different cases (A, C, D)

The differences in outcomes resulting from four different fence spatial layouts demonstrate that their flood regulation function within the site can essentially be understood as: porous fences influence the site's spatial connectivity through various boundary resistances. Under the current conditions (Case A), the highest connectivity exists between the site interior and exterior, allowing smooth water flow in and out. Peak flow is primarily determined by inflow discharge, terrain gradient, and various internal obstacles within the site. Adding a wall on the west side (Case B) introduces an additional barrier to the connected space. However, since the wall runs parallel to the primary flow direction, its obstruction effect is minimal, resulting in only a slight decrease in water depth within the site. The scenario with walls on the west and north sides (Case C)

increases resistance directly facing the inflow direction while maintaining downstream spatial connectivity, thus not disrupting normal water discharge. This layout slightly reduces peak flood levels and water retention duration within the site. However, the consequence outside the site (upstream of the fence) is enhanced bypass flow around the walls and significant localized water level elevation, common side effects of rigid protection measures. In contrast, the fully enclosed porous fence layout (Case D), incorporating walls on the west, north, and south sides, directly disrupts spatial connectivity. This significantly increases boundary water exchange resistance, making it difficult for water to drain once it enters the site. Consequently, notable water retention effects occur both inside and outside the site. This indicates that the porous fence in the Katsura Imperial Villa case did not demonstrate stable and significant positive flood reduction efficacy. Its function exhibits high spatial layout sensitivity and risks of side effects.

Overall, the porous fence in this case did not demonstrate the expected significant flood reduction effectiveness, while instead exhibiting undeniable negative impacts. Its primary flood mechanism involves significantly raising water levels upstream and producing only minimal flood peak delay and water depth reduction downstream. The main effect is limited improvement in average indicators for protected areas, coupled with a high probability of creating higher-risk zones in surrounding areas, resulting in greater overall losses. These findings indicate that implementing porous fences, particularly in floodplains, must be approached with caution, carefully weighing the potential risks to both upstream and downstream areas. However, when upstream areas are permeable green spaces or secondary zones harmonizing with the environmental landscape, porous walls can still serve as a low-impact micro-adjustment tool. When combined with measures like rain gardens, they can provide limited optimization of inundation extent and water depth distribution during minor to moderate flood events. This offers critical structures a small margin of water depth and a window of time for emergency response. Preliminary design principles for porous fences are summarized as follows:

- 1) Identify the primary inflow direction and main outflow path in advance to support subsequent porous fence layout design.

2) The closer the angle between the fence and inflow direction approaches 90 degrees, the stronger the flow resistance. The closer it approaches 0 degrees, the closer it is to no resistance. Angle selection depends on balancing upstream and downstream risks.

3) Install controlled openings along the dominant outflow direction to maintain water flow pathways and avoid fully enclosed configurations.

4) Consider the distance between fences and buildings. The effectiveness of fences diminishes progressively with increasing distance, regardless of upstream or downstream location.

5) Thoroughly evaluate the increased risks from upstream water elevation against the limited benefits of downstream mitigation. Avoid decisions focused only on protecting specific assets.

Additional notes: The design principles outlined above were derived from comparative numerical simulations conducted on the actual site of Katsura Imperial Villa. These conclusions may be influenced by complex site conditions, resulting in unclear and unstable performance among the compared schemes. The porous fence's dominant role in this case study is difficult to clearly isolate and extract due to the overlapping presence of numerous factors in the real-world scenario (micro-topography, local flow convergence lines, inflow and outflow pathways, site obstacles, and roughness coefficient variations). To provide explainable mechanistic support and refine clear design guidelines for practical scenarios, future research will introduce numerical simulations under idealized layout configurations. For instance, under controlled variables, studies will examine how layout conditions, such as the fence's angle relative to the main flow direction, the position and layout of downstream openings, and the relative distance to protected structures, individually influence the hydrodynamic response of porous fences. This will establish comprehensive design reference criteria for porous fences.

6.5. Summary

1) This chapter builds upon the hydrodynamic influence mechanism research and validation of heritage architectural features conducted in Chapters 4 and 5. Focusing on real-world heritage-scale application needs, it accomplishes three key tasks: first, it

establishes the CEI framework to quantify and balance critical protection effects against environmental external impacts within heritage sites; second, within this framework, it investigates the spatial distribution and effectiveness of flood mitigation for two passive flood-adaptive architectural designs, including piloti and porous fences. Third, it engages in optimization design discussions for real heritage scenarios, translating the hydrodynamic mechanisms identified in the previous chapters into practical management insights and design implications for future applications.

2) The CEI indicator system incorporates a layered approach, focusing on three core metrics: maximum water depth, exposure duration, and cumulative hazard. It categorizes heritage sites into two evaluation levels, architectural attributes and landscape attributes, and employs a unified calculation process to achieve normalized quantification across multiple measures and levels. This framework emphasizes the accurate representation of spatial variations and risk redistribution induced by passive measures. It provides a research tool for comprehensively balancing protective efficacy within target zones and mitigating adverse impacts on surrounding areas, thereby serving heritage disaster management and contemporary design decision-making.

3) This chapter integrates the flood-adaptive measures validated in Chapters 4 and 5 into a quantitative assessment of flood mitigation effects in heritage environments, using Katsura Imperial Villa as a case study. The benefits of piloti structures are more concentrated on disaster reduction within the building area, with relatively minor impacts on the surrounding landscape. While unlikely to be applied to heritage conservation design, they offer significant resilience insights for waterfront space design. In contrast, Katsura Imperial Villa's existing porous fence exerts a slight adverse effect on the current urban flood pattern. Due to mismatched flow directions with the fence layout, the overall flood risk within the heritage zone shows a minor increase. This demonstrates the fence's high sensitivity to upstream and downstream spatial configurations. Under certain conditions, upstream impacts may become more apparent, requiring cautious implementation and comprehensive assessment in real-world settings.

4) Finally, the study further explores the optimization design of porous fences for Katsura Imperial Villa. Through comparative simulations of different layouts, it identifies

the fundamental mechanism by which porous fences function: by providing boundary resistance to restrict spatial connectivity within the site. The porous fence exhibits significant spatial layout sensitivity. While it may offer limited peak reduction or flood duration improvement downstream, it is more likely to induce upstream flooding effects. Therefore, comprehensive assessments of both architectural and landscape layers are essential during design comparison. Overall, this chapter translates the mechanism insights and validation results from Chapters 4 and 5 into more practically meaningful risk assessments and design implications at the heritage site scale.

7. Conclusion

This study focuses on the coupling between hydrodynamic processes and architectural spatial features in Kyoto's cultural heritage contexts. It aims to address the need for detailed flood simulation at the building scale for heritage conservation, while overcoming the limitations of traditional passive flood-adaptive design, and its lack of mechanism explanation and effectiveness evaluation in contemporary contexts. Organized around six levels including spatial feature extraction, hydrodynamic impact analysis, numerical model construction, mitigation mechanism analysis, mitigation effect quantification, and resilience optimization design, this study translates their influence on flood dynamics into parameter expressions compatible with 2D hydrodynamic equations. Using piloti and porous fence as representative spatial features, comparative simulations and flood mitigation mechanism analyses are conducted at the heritage site scale. These findings subsequently support comprehensive efficacy evaluations of passive measures and resilient optimization design.

7.1. Main findings

7.1.1. Modeling for coupling flood hydrodynamics with architectural features

At the methodological level, this paper develops a two-dimensional hydrodynamic modeling approach specifically tailored for heritage scenarios. The research demonstrates a methodological pathway for translating heritage spatial features into hydraulic parameters, enabling them to be incorporated into the governing equations of numerical models and directly participate in hydrodynamic calculations. Specifically, for piloti, a slot-extended model suitable for 2D unstructured mesh was established to characterize mixed flow conditions. This translates the elevated space into a numerically simulatable flow channel, with the accuracy of the numerical model validated through flume experiments. For porous fences, experimental inversion and empirical equation fitting integrated local drag terms with associated drag coefficients into SWEs, enabling the physical mechanism-based representation of flow resistance generated by fences of varying porosity within the inundation model. Compared to conventional simulations that neglect architectural components, this study enhances the applicability of 2D

hydrodynamic models for heritage site flood simulation by accounting for the influence of building spatial features on flood behavior. This establishes a standardized modeling foundation for subsequent research. Additionally, it provides a valuable interdisciplinary pathway for further collaboration between architecture and hydraulics.

7.1.2. Hydrodynamic mechanisms and risk redistribution at heritage sites

At the mechanism level, comparative simulations at the heritage site scale reveal that piloti and porous fences exert different but equally significant hydrodynamic effects on flood dynamics. For piloti, their core function lies in altering flow paths around structures by increasing water passageways and elevating functional layer heights, thereby significantly mitigating peak water depths within the building area. Although flow velocities slightly increase in most zones, they remain predominantly low, contributing minimally to overall hazard levels. However, isolated high-velocity points in certain areas require separate verification for structural stability. For porous fences, their typical effects include significant upstream water level elevation due to added resistance, along with minor downstream peak reduction and delay. Their impact varies based on the relationship between inflow direction and spatial layout. These results indicate that passive measures within heritage sites do not directly mitigate disasters. Their fundamental mechanism involves spatially redistributing risk by reorganizing the local flow field.

7.1.3. Effectiveness assessment and implications for resilient design

In quantifying flood mitigation effects, this study establishes the Comprehensive Effectiveness Index system. This framework employs a uniform hydrodynamic indicator-based approach to compare flood intensity and process changes before and after traditional measures. It comprehensively evaluates both the structure itself and the surrounding landscape environment, enabling the full presentation of disaster reduction benefits and potential costs. CEI evaluation results indicate that piloti exhibit a significant positive effect at the building level, while minor negative effects on landscape. This suggests that when applying piloti to contemporary floodplain urban and architectural design, attention should be paid to the differentiated effects at the building and landscape

levels. For porous fences, critical discussion should focus on how to control their application limits. Under certain layout conditions, fences may offer slight inundation mitigation in critical areas. However, the more significant consequence may be upstream water retention, potentially multiplying risks. Therefore, when employed as heritage resilience measures, exceptional caution is required, with case-specific balancing of upstream risks against downstream benefits. The proposed model and evaluation system provide quantitative methodological tools for optimizing design alternatives.

7.2. Limitations and future work

Although this paper has achieved breakthrough progress in the parameterized representation of spatial features, detailed inundation simulations of heritage scenarios, and indicator-based evaluation, limitations remain in historical data collection, model application constraints, the scope of evaluation applicability, and coverage of architectural characteristics. These areas require ongoing exploration and refinement in future work:

1) Lack of historical flood event data

Although the foundational inundation model employed in this study has been validated through numerous real-world flood event analyses, the unique nature of cultural heritage sites makes historical disaster data difficult to obtain. Consequently, the models for Katsura Imperial Villa and Shimogamo Shrine lack validation based on historical records. Nevertheless, the core mechanisms of the 2D slot-extended model as well as the empirical C_d equation and drag force incorporation have been validated. Consequently, the scenario comparison simulations and effectiveness evaluations conducted in this study remain reliable and valuable.

2) Limited component-level risk resolution

This study identifies inundation intensity through 2D hydrodynamic processes but struggles to assess stress, scouring, and damage to critical components. Future work will develop component-level hydrodynamic models (Li et al., 2025) and apply 3D modeling (Dellinger et al., 2025) to enhance resolution for heritage building component-level risks.

3) Research limitations of porous fences

Current drag coefficient calculations rely on simplified steady-state experimental conditions. However, the actual equivalent drag of porous fences may exhibit time-varying behavior with changes in water depth and flow velocity. Future work should address this through more comprehensive temporal designs and supplementary experimental measurement equipment. Additionally, the practical effectiveness of porous fences is influenced by multiple factors. Numerical simulations of controlled variables for idealized layouts could further validate their design rationale.

4) Site dependency of CEI evaluation method

CEI assessments exhibit significant site dependency, influenced by both natural and artificial environmental conditions alongside engineering parameters. Consequently, evaluation results apply only to specific cases. To derive more universally applicable flood mitigation conclusions, comparative assessments and uncertainty analyses across diverse site types are required.

5) Further modeling expansion

The heritage inundation modeling in this study focuses specifically on overhanging eaves, piloti structures, and porous fences extracted from typical heritage sites in Kyoto City. It has not yet systematically covered additional architectural and structural features that directly influence flood behavior in other regions or cases. Future work will increasingly refine adaptive flood inundation modeling for diverse heritage sites, using the established conversion pathway from heritage features to hydraulic parameters as a methodological reference.

6) From hydrodynamic effects to structural safety assessment

This study primarily focused on quantifying hydrodynamic indicators, but it did not explicitly convert these hydrodynamic outcomes into external loads or structural safety calculations. In heritage buildings, specific spatial features and component layouts may, under certain conditions, increase local head differences and pressure gradients, thereby intensifying flood-induced additional loads. A rigorous safety assessment therefore requires translating hydrodynamic outputs into structural loading conditions and external actions, in order to further evaluate the stability of heritage structures under extreme inundation scenarios.

This study establishes an interdisciplinary research pathway between architecture, hydrodynamics, and disaster science. It not only enhances our quantitative understanding of the scientific essence of traditional wisdom but also provides reusable numerical tools and methodological paradigms for the preventive conservation and precise risk assessment of cultural heritage facing increasingly severe flood disasters. This framework demonstrates strong expansibility, allowing future exploration of integration with additional architectural features or future climate scenarios to continually enhance the adaptability of flood simulations for heritage sites. The outcomes of this work not only provide quantitative validation of traditional architectural wisdom but also offer valuable historical insights for designing sustainable and resilient future cities.

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