Development and Experimental Validation of a Slot-Extended 2D Hydrodynamic Model for Piloti Structure in Heritage Sites

〇Xi CHEN, Kenji KAWAIKE, Takahiro KOSHIBA, Keiko WADA

1. Introduction

A consensus is emerging on the significance of flood dangers to cultural properties under climate change (IFRC, 2014; Sesana et al., 2021). However, hydrodynamic models capable of predicting fine-scale flow fields at the heritage-site scale remain insufficiently developed. Notably, numerous heritage structures located in floodplains embody flood-adaptive measures as identifiable architectural features, such as piloti structures, permeable walls, and retention spaces. These resilience measures redistribute flow and affect flood behavior by elevating habitable floor, adjusting boundary permeability and storage capacity, thereby enabling coexistence between heritage and floods (Blavier et al., 2023; Liao et al., 2016; Okubo, 2016). These practical problems further highlight the dual importance of developing hydrodynamic models that explicitly account for architectural features, both for high-precision flood simulation at heritage sites and for a scientific understanding of traditional flood-mitigation measures.

Consequently, piloti is selected as a representative heritage feature. Piloti denotes a structural design in which the ground floor is elevated and sustained by columns or shear walls (Liao et al., 2016). At Katsura Imperial Villa in Japan, piloti functions both as a significant heritage element and a flood-adaptive design (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). Comparable practices are also widespread across global floodplains

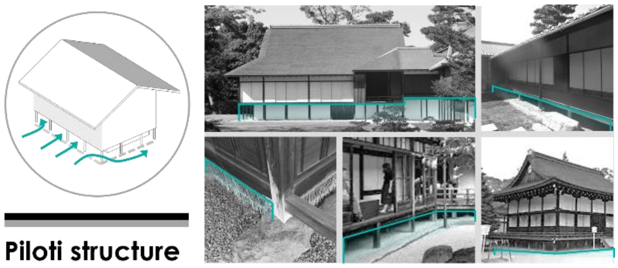

Fig.1 The diagram of Piloti

This study introduces a slot-extended 2D hydrodynamic model tailored for heritage sites with typical piloti features. The model illustrates the hydraulic response of flow through piloti by employing a 2D virtual slot that enables the transition from unpressurized to pressurized flow. The extended model is first validated through laboratory experiments and then applied to the Katsura Imperial Villa with comparative simulations under conditions with and without piloti.

2. Methodology

In order to develop a flood inundation model capable of representing the characteristics of piloti at the heritage site, this research outlines two main methods: (i) developing a slot-extended 2D hydrodynamic model (ii) validating the effectiveness of its core innovative component (2D Slot-Extended) through flume experiments.

The inundation model in this study extends a 2D hydrodynamic framework (Kawaike, 2002) on unstructured meshes to better represent complex heritage-site geometries and piloti footprints. Piloti–flood interaction involves a transition from unpressurized flow to pressurized flow, which classical 2D shallow water equations cannot capture directly. To address this limitation, the Preissmann Slot concept is incorporated into a 2D unstructured-mesh setting.

Laboratory flume experiments were conducted to validate the accuracy of the slot-extended model. The experiments were conducted at the Ujigawa Open Laboratory, measuring water levels across five different inflow discharges (Fig. 2).

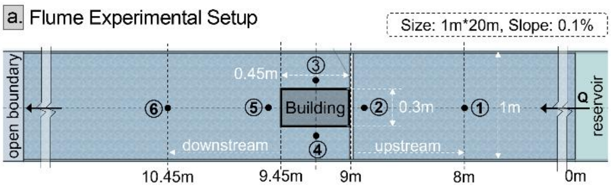

Fig.2 The flume experiment setup

3. Results and Discussions

This research at first employs flume experiments to validate the slot-extended 2D hydrodynamic model for both steady and unsteady conditions(Fig. 3). The results indicate a strong correlation between experimental and simulated data, as well as a superior alignment of flood processes, thereby validating the model for future use.

At the same time, an error rise trend was seen in the water depth in front of the building's upstream facade as the discharge increased. One possible hypothesis suggests that the model undervalues the resistance in the elevated floor, which could potentially include the effects of ceiling friction. Future studies could include additional friction or resistance parameters to improve model precision.

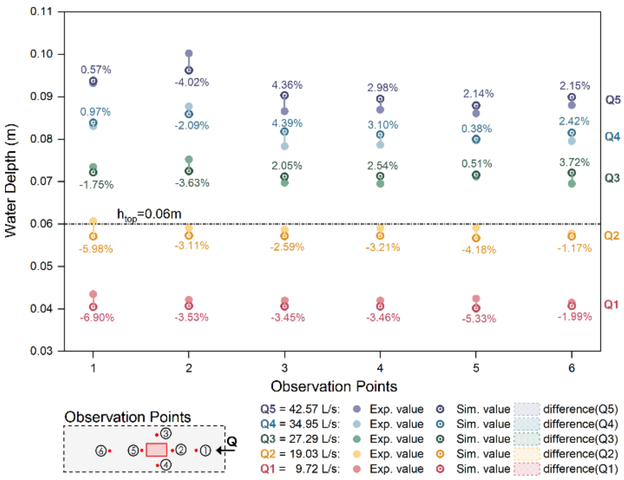

Fig.3 Comparison of experimental and simulation results

The validated slot-extended model was employed to simulate floods across two scenarios in Katsura-Rikyu: the actual with-piloti scenario and a hypothetical without-piloti scenario. In the buildings area, water depths are considerably reduced when piloti are considered, with the depth boundary aligning closely with the footprints of the buildings. This illustrates the influence of piloti on simulation results (Figs. 4b and 4c). However, in the scenario with-piloti, maximum velocities occur at certain building corners near the lake, creating a wake pattern that diminishes along the slope of the terrain, an occurrence that does not happen without piloti (Figs. 4d and 4e).

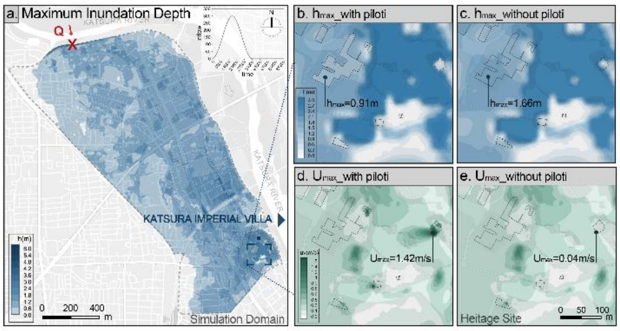

Figure 4. Simulation result of the Katsura Imperial Villa, comparing with (left) and without (right) porous hedge over time

4. Conclusions

- A slot-extended 2D model was developed to simulate mixed free-surface/pressurized flow beneath piloti and resolve heritage-scale building features; flume tests verified its accuracy.
- At Katsura Imperial Villa, piloti significantly reduced peak water depth in building areas, while velocity increases were generally negligible except at a few localized spots.

References:

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2) Maranzoni, A., Dazzi, S., Aureli, F., Mignosa, P., 2015. Extension and application of the Preissmann slot model to 2D transient mixed flows. Adv. Water Resour. 82, 70–82.