Forces on buildings with openings and orientation in a steady post-tsunami free-surface flow

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ABSTRACT

Steady free-surface flows around buildings occurring during flood or tsunami events can produce major damages and a quantification of the post-peak forces is essential for safety and resilience of coastal structures. The loading process is highly affected by the flow Froude number and the drag coefficient, commonly defined for highly subcritical flows, while field observations of tsunami flows reported Froude numbers close to one, visually appearing as a choked regime. The present experimental study addresses the hydrodynamic forces on emerging buildings in a subcritical choked regime, focusing on the effect of openings and orientation. Laboratory experiments indicated a substantial difference in flow depths between the up- and downstream side of the building for increasing Froude numbers. The presence of openings induced a flow through the building lowering the difference in flow depth, limiting the effect of the hydrostatic component of the loading process. The formulation of an empirical resistance coefficient C_R allowed a combination of both form drag and hydrostatic forces. Whilst for impervious buildings C_R was consistent with reference studies, for buildings with openings C_R was directly dependent upon porosity. Contrarily to the unsteady flow conditions, results showed that the sidewalls also played a role in the loading process. Buildings with a rotated orientation resulted in slightly larger surfaces exposed to the flow and larger horizontal forces. Nevertheless, these were applied at lower cantilever arms, thus reducing the tilting moment. Altogether, this study provides experimentally-derived parameters that will support hydraulic engineers in the design of coastal structures.

1. Introduction

Uncontrolled flows can be harmful to structures. In the built environment, these flows can be expected during floods, tsunamis propagating inland, storm surges, impulse waves or dam-break waves. Dreadful examples were observed in the 2004 Indian Ocean tsunami, the 2005 inundations generated by Hurricane Katrina, the 2011 the Tohoku Japan tsunami and most recently in the 2018 Sulawesi tsunami in Indonesia (Dias et al., 2006; Roeber and Bricker, 2015; Chock et al., 2012; Mikami et al., 2019). Although rare, recent events allowed to assess the hydrodynamic behavior of tsunamis propagating inland, focusing on inundation depths and velocities. Visual observations revealed flow depths between 4 and 7 m in the southern part of Khao Lak, Thailand, during the 2004 Indian Ocean tsunami (Dias et al., 2006) and velocities as high as 10–13 m/s near the Sendai Airport during the 2011 Tohoku, Japan, tsunami (Jaffe et al., 2012). Fritz et al. (2012)

reported Froude numbers $Fr \approx 1$ for tsunami flows propagating inland. Recent field studies on the Sulawesi tsunami (Indonesia, 2018) revealed inundation depths up to 4.82 m in Taman Ria and 6.80 m in Buluri (Mikami et al., 2019).

Because of their long wavelengths and periods, tsunamis propagating inland are commonly modelled using dam-break waves, vertically released discharges and pump-driven flows (Chanson, 2006; Wüthrich et al., 2018a; Goseberg et al., 2013). For these flows, the initial unsteady propagation of the front is followed by a relatively long post-peak hydrodynamic phase, where the assumption of steady-flow conditions is acceptable.

Tsunamis propagating inland are responsible for severe destruction and recent field surveys in Silae and Buluri (Indonesia) in 2018 revealed that most buildings within 80–100 m from the shoreline were highly damaged (Mikami et al., 2019). Many structures collapsed during the impact of an incoming wave, but others suffered from major damages

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initiated by the subsequent quasi-steady flow around the building.

The hydrodynamic comportment of impervious buildings in an open channel flow is well established. Among others, the contributions of Nagler (1918), Yarnell (1934), Benjamin (1956) and Raju et al. (1983) serve as references. Riviere et al. (2017) studied the behavior of buildings subjected to supercritical open-channel flows, detailing some key features of the bow waves on the upstream side of the building, while Mignot et al. (2016) focused on the scour around the buildings. Qi et al. (2014), investigated the forces exerted by a steady subcritical flow on an emerging building, pointing out that the drag coefficient depended on its shape, the blockage ratio $\beta = B/W$ (B is the transversal building width and W the channel width, $W = 1.4$ m in the present study), the ratio between the upstream flow depth h and B (i.e. h/B), and the flow Froude number Fr (Eq. (3)). The dependence of the drag coefficient C_D on the Reynolds number is commonly assumed to be weak because of the highly turbulent nature of most open-channel flows, both in the laboratory and in the field. Most drag coefficients in literature were derived from the loss of momentum flux through flow depths measurements (Henderson, 1966). Qi et al. (2014) concluded that this technique is not suitable for 3-dimensional buildings because of the time-dependent wave patterns. Further, the drag coefficient is typically defined for very low Froude numbers with similar upstream and downstream flow depths. A selection of previous experimental tests on forces acting on free-standing buildings is presented in Table 1.

The behavior of buildings during flood events was discussed by Cuomo et al. (2009), pointing out the need for updated risk assessment methods and studies on the vulnerability of key infrastructures. Numerical and experimental studies showed that the interaction of tsunamis propagating inland with the built environment resulted in differences in flow depths and flow velocities, thus implying that the Froude number was influenced by the location (Cox et al., 2008; Park et al. 2013; Goseberg, 2013).

The importance of a safe design for tsunami-events was emphasized by Chock et al. (2012) after the 2011 Japan Tohoku tsunami, and preliminary studies by Faisal et al. (2018) pointed out the importance of openings in limiting flood-induced loads. The presence of break-away walls was also identified as a useful measure to circumvent extra loading on structures during floods and tsunami events (ASCE7-6, 2016). Thus, the effect of building geometry and openings becomes predominant during the hydrodynamic phase, when breakaway walls and inner obstacles have been washed away by impact forces. In addition, recent field surveys in Taman Ria (Palu, Indonesia), showed that a

porous multi-storey shopping mall and parking garage acted as vertical shelters, saving people's lives (Mikami et al., 2019). A detailed characterization of the loading process in terms of forces and inundation depths is also fundamental to determine the fragility curves of coastal buildings (Xiong et al., 2019; Jansen et al., 2020).

Most previous studies focused on impact forces generated by highly unsteady flows, and little interest was given to the loading process of buildings with openings under post-peak, steady, subcritical flow conditions. This points at a gap in knowledge in the estimation of inundation depths, flow-induced forces and moments. Thus, the objective of this paper is to provide a characterization of the loading process of buildings with and without openings and different degrees of orientation, under controlled steady flow conditions. An understanding of the hydraulic and structural behavior of coastal buildings under steady flow conditions is essential for the safe design of resilient structures.

2. Forces on buildings

The horizontal streamwise force F_x acting on an impervious building is proportional to the difference in momentum between the upstream and the downstream control sections (Fenton, 2003, 2008). As such, if viscous and friction stresses are neglected, the total drag (or hydrodynamic) force F_x is given by:

$$F_x = \rho(M_1 - M_d) = \frac{1}{2}\rho g W (h_1^2 - h_d^2) + \rho W (v_1^2 h_1 - v_d^2 h_d) \quad (1)$$

where ρ is the water density ($\rho = 1000$ kg/m³), g the gravity constant ($g = 9.81$ m/s²), W the channel width, h_1 , h_d and v_1 , v_d upstream and downstream water depths and velocities, respectively (Fig. 1). M is the momentum flux, defined as $M = (h v^2 + 0.5 g h^3) \cdot W$. A simplification of Eq. (1) leads to the sum of a form drag and a hydrostatic component:

$$F_x = \frac{1}{2} C_D \rho B h v^2 + \frac{1}{2} C_H \rho g B (h_1^2 - h_d^2) \quad (2)$$

where C_D and C_H are constants determined experimentally and B the transverse building width (Fig. 4). The Froude number Fr_1 refers to the upstream flow (Fig. 1) defined as:

$$Fr_1 = \frac{v_1}{\sqrt{g h_1}} = \frac{Q}{h_1 W \cdot \sqrt{g h_1}} \quad (3)$$

where Q is the discharge. Low upstream Froude numbers assured that

Table 1

List of selected studies on forces acting on free-standing buildings.

Study	Building width B	Orientation	Blockage ratio B/W	Flow conditions	Note
Nouri et al. (2010)	0.2 m	$\theta = 0^\circ$	0.15	Unsteady	Free standing building Impervious Frontal
Qi et al. (2014)	0.05–0.20 m	$\theta = 0^\circ$	0.10–0.40	Steady	Free standing building Frontal
Shafiei et al. (2016)	0.30 m 0.41 m 0.42 m	$\theta = 0^\circ$ $\theta = 30^\circ$ $\theta = 45^\circ$	0.25 0.34 0.35	Unsteady	Free standing building Impervious Frontal + rotated
Zhou et al. (2016)	0.05–0.25 m		0.06–0.33	Steady	Array of buildings
Foster et al. (2017)	0.18, 1.08, 1.44 m	$\theta = 0^\circ$	0.1, 0.6 and 0.8	Unsteady	Free standing building Impervious Frontal
Riviere et al. (2017)	0.2, 0.75 m	$\theta = 0^\circ$	0.02–0.2	Steady	Free standing building Impervious
Wüthrich et al. (2018b, c)	0.3 m	$\theta = 0^\circ$	0.21	Unsteady	Free standing building Impervious Frontal
Asadollahi et al. (2019a,b)	0.30 m 0.39 m 0.42 m	$\theta = 0^\circ$ $\theta = 22.5^\circ$ $\theta = 45^\circ$	0.23	Unsteady	Free standing building Impervious Frontal + rotated
Present study	0.30 m 0.39 m 0.42 m	$\theta = 0^\circ$ $\theta = 22.5^\circ$ $\theta = 45^\circ$	0.21 0.28 0.30	Steady	Free standing building With and without openings Frontal + rotated

Fig. 1. Experimental set-up, coordinate system, and definition of the main variables.

$Fr_1 \approx Fr_d \approx Fr_2$. Consequently, the difference in flow depth between the upstream h_1 and downstream h_d sections is negligible and the hydrostatic force irrelevant (right term in Eq. (2), Qi et al., 2014). The empirical drag coefficient C_D is commonly defined for low upstream Froude numbers ($Fr_1 \rightarrow 0$) and is a function of the blockage ratio β . For increasing discharges, the upstream Froude number Fr_1 tends to a characteristic value Fr_{1c} and the flow becomes “choked”. If $Fr_1 \rightarrow Fr_{1c}$ then the difference in flow depth becomes non-negligible ($h_1 \gg h_d$). Qi et al. (2014) concluded that, even in the choked regime, the majority of the drag is form drag, whose intensity was weakly affected by the blockage ratio $\beta = B/W$. The hydrostatic component became important only for high blockage ratios.

The empirical drag coefficient C_D is commonly derived based on experimental studies. The behavior of C_D under subcritical steady conditions is $C_D = 2.0$ for squared impervious buildings (Blevins, 1984). For wave impacts under unsteady flows, the laboratory experiments by Arnason (2005) suggested $C_D = 2.0$ for a square prism with orientation $\theta = 0^\circ$ (frontal impact). This value is also adopted by FEMA55 (2000). Yeh (2006) noted that $C_D = 2.0$ was appropriate for steady flow conditions, but he did not directly apply them to tsunami flows. For these, $C_D = 3.0$ was suggested to take into account the impulsive component of the loading exerted by the wave front, an aspect excluded herein. If a long tsunami period is considered, then the assumption of quasi-steady conditions is realistic and the drag force in Eq. (2) can be applied if an appropriate C_D is used. Shafiei et al. (2016) isolated the hydrodynamic force component by subtracting the hydrostatic force from the total force, leading to $C_D = 1.65$ for frontal impacts. Gupta and Goyal (1975), Chaplin and Teigen (2003), Arnason (2005), Wüthrich et al. (2018b) and Ghodoosipour et al. (2019) combined both hydrostatic and hydrodynamic components into a resistance coefficient $C_{R,0} = 2.0$ for highly unsteady wave impacts on impervious structures. This methodology represented a simplified approach, useful for practical purposes. Wüthrich et al. (2018c) showed a good agreement between horizontal forces and the wave’s momentum flux per unit width ($h v^2$). In addition, Wüthrich et al. (2018b) investigated the effect of openings on the resulting hydrodynamic load in unsteady flows, showing a linear reduction of the total force as

$$F_x = \frac{1}{2} \rho \cdot (C_{R,0} \cdot \Pi) \cdot B \cdot h_1 v_1^2 \quad (4)$$

where $C_{R,0}$ is a resistance coefficient defined for the frontal impervious building considering both the hydrostatic and the drag components. In Eq. (4), Π is a porosity coefficient taking into account the openings on both the front- and back-side of a building via the porosity P defined as

$$\Pi = 1 - \min[(P_h)_{\text{front}}; (P_h)_{\text{back}}] \quad (5)$$

Eqs. (4) and (5) allow to estimate the total impact load acting on the building from the wave hydrodynamic properties and building geometry. The loading on inner walls in residential houses was investigated by Moon et al. (2020), confirming the complicated dynamics of tsunami flows within residential buildings.

3. Experimental set-up

A set of experiments was conducted in the Laboratory of Hydraulic Constructions (LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. The same facility was previously used by Wüthrich et al. (2018a,c,b). The emerging structures (similar to residential buildings) were installed in a horizontal channel with a length of 15.5 m and a width of $W = 1.4$ m, leading to a blockage ratio of $\beta = B/W = 0.21$, which is consistent with literature and previous studies (Table 1). Coastal buildings are commonly found in highly populated areas, where blockage ratios of $\beta = 0.2$ – 0.3 are not uncommon. The channel friction was estimated to be equal to a Darcy-Weisbach friction factor $f \approx 0.02$, corresponding to a roughness $k_s \approx 0.66$ mm. The steady discharge Q was provided by the pumps of the closed laboratory circuit. The flowmeter was calibrated prior to the tests and its measurements error was below 1% FS (Wüthrich, 2018). The experimental set-up and the main parameters involved are presented in Fig. 1.

The buildings were cubical with a side length $B = 0.3$ m, obtained by assembling aluminum plates with a thickness of 0.01 m. If a geometric scaling ratio of 1:30 is assumed, these corresponded to three-floor residential houses often observed on coastal areas. Note that for the range of discharges tested herein the buildings were never overtopped, thus the building height was irrelevant. Some simple push-over FEM numerical simulations were conducted using the commercial software *Diana FEA*, providing an estimation of the building stiffness ranging between $6.34 \cdot 10^6$ and $1.72 \cdot 10^7$ N/m. Laboratory hammer tests reported Eigen-frequencies between 41 and 43 Hz (model scale). These values were sufficiently high to consider the building as fully rigid, thus avoiding any significant fluid-structure interaction and resonance (Wüthrich, 2018).

Six building porosities were tested (Fig. 2), ranging between $P_{\text{tot}} = 0$ (impervious, reference) and 60% (highly permeable). Note that two internal floors were added for all configurations to provide a better representation of reality. Two porosities ($P_{\text{tot}} = 31$ and 42%) had a non-homogeneous distribution of the openings, with more openings in the lower part of the building. The porosity P_h faced by the upstream flow depth h_1 was defined as the ratio between the surface of the openings A_o and the total building surface exposed to the flow :

$$P_h = \frac{A_o}{B \cdot h_1} \quad (6)$$

Fig. 2. Total building porosities. (The impervious building with $P_{tot} = 0\%$ is not shown).

if $h_1 = B$ then the total porosity $P_h = P_{tot}$ is found.

As shown in Fig. 3, three building configurations were tested for the orientation $\theta = 0^\circ$ (frontal impact):

- i. All porous sides (0): openings equally distributed on all four sides.
- ii. Impervious sides (F): openings on the front and back, impervious sides.
- iii. Impervious back (B): openings on the front and both sides, impervious back.

Three impact orientations were tested, namely $\theta = 0^\circ$ (frontal, reference), 22.5° and 45° (Fig. 4). Due to symmetry, Shafiei et al. (2016) showed that buildings with impact orientations $45^\circ < \theta < 90^\circ$ had similar results to those with $0^\circ < \theta < 45^\circ$. Additional configurations resulted from the combination of building orientations ($\theta = 0^\circ$, 22.5° and 45°) and total porosities ($P_{tot} = 0, 17, 31, 34, 42$ and 60%), as detailed in Table 2.

Flow depths were measured with five Ultrasonic Distance Sensors (US), type Baumer UNAM 30I6103, with an acquisition frequency of 12.5 Hz and a precision of ± 0.5 mm. The buildings were fixed on a dynamometric Force Plate (AMTI MC6-1000) measuring time histories of forces and moments in all three directions with a frequency of 1 kHz and a precision of ± 0.5 N. The set-up, location of the instruments and the reference system are shown in Fig. 1.

4. Methodology

The test program is presented in Table 2. For each configuration a minimum of 10 discharges was tested, ranging between 23.1 and 170 l/s, for a duration of $\Delta t = 60$ s. This was sufficiently long to capture the main parameters. Note that the data used herein were not collected during wave impact tests, but a separate test campaign was conducted with exclusively steady flow conditions. Both horizontal force F_x and moment M_y were time-averaged over the whole duration ($\Delta t = 60$ s). Similarly to Qi et al. (2014), the incoming flow was sub-critical and the presence of the building generated a backwater effect. This resulted into

flow depths h_1 that were higher than those under uniform conditions. Without the building, the uniform flow had an average $Fr_1 \approx 0.84$. Note that the rotation of the building by θ resulted into larger projected widths in the transversal direction, i.e. $B = B_{\theta=0}(\sin \theta + \cos \theta)$, resulting into larger blockage ratios ($\theta = 22.5^\circ \rightarrow \beta = 0.28$; $\theta = 45^\circ \rightarrow \beta = 0.30$), as detailed in Table 2.

5. Flow features around the buildings

Previous model studies considered pronounced subcritical flows both upstream and downstream, with similar Froude numbers ($Fr_1 \approx Fr_2 \approx Fr_d$, Eq. (3) and Fig. 1). When the upstream Froude number Fr_1 approached a certain characteristic value Fr_{1c} , then the downstream Froude number Fr_d increased significantly (Qi et al., 2014). The flow depth h_d behind the building decreased and a hydraulic jump occurred, as shown in Figs. 5a and 6a. This set the beginning of the choked regime.

The flow around the impervious building ($P_{tot} = 0\%$) is shown in Fig. 5a, where small surface oscillations were observed on the upstream side. The incoming subcritical flow deviated progressively around the structure, revealing streamlines in the form of a horseshoe (Dargahi, 1989; Mignot and Riviere, 2010). Bow waves were observed on the upstream side of the building, similar to those reported by Goseberg and Schlurmann (2014) for transient flows. The presence of the building also induced a backwater effect in the upstream side of the channel. The flow depth reduced along the impervious lateral sides of the building as the flow accelerated. Downstream of the building, reduced flow depths were observed and the Von Kármán vortex street was overlaid by a V-shaped hydraulic jump (Fig. 5a). The observations were consistent with those of Qi et al. (2014) and Riviere et al. (2017).

The presence of openings (Configuration 0, Fig. 5b,c,d) established a seepage flow through the building, modifying the dynamic of the flow. Little differences between porous and impervious configurations were observed on the upstream flow surface, where streamlines in the form of a horseshoe were still observed (Fig. 5b). However, major differences attributed to the presence of openings occurred at the downstream side, where constantly higher flow depths appeared. Because of the interaction between the discharge through the building and the flow around it,

Fig. 3. Building configurations, here shown for $P_{tot} = 34\%$.

Fig. 4. Impact orientation for the impervious building ($P_{\text{tot}} = 0\%$, top), and for a total building porosity $P_{\text{tot}} = 60\%$ (bottom).

Table 2

Experimental program.

Building orientation θ [°]	Building configuration (Fig. 3)	Total Building porosity P_{tot} [%]	Discharge Q [l/s]	Fr_1 (with building)	$Re = \frac{\rho v_1 h_1}{\mu}$	Blockage ratio β
0°	All porous sides (O)	0, 17, 31, 34, 42, 60	23.1–170	≈ 0.44 –0.65	1.0 – $4.2 \cdot 10^5$	0.21
0°	Impervious sides (F)	0, 17, 31, 34, 42, 60	23.1–170	≈ 0.44 –0.65	1.0 – $4.2 \cdot 10^5$	0.21
0°	Impervious back (B)	0, 17, 34, 42, 60	23.1–170	≈ 0.44 –0.65	1.0 – $4.2 \cdot 10^5$	0.21
22.5°	All porous sides (O)	0, 17, 31, 34, 42, 60	23.1–170	≈ 0.44 –0.65	1.0 – $4.2 \cdot 10^5$	0.28
45°	All porous sides (O)	0, 17, 31, 34, 42, 60	23.1–170	≈ 0.44 –0.65	1.0 – $4.2 \cdot 10^5$	0.30

Note: θ = angle orientation, P_{tot} = total porosity, Q = discharge; Fr_1 = upstream Froude number, Re = Reynolds number, ρ = water density, μ = water dynamic viscosity, v_1 = upstream flow velocity, h_1 = upstream flow depth and β = blockage ratio.

a high level of turbulence with intense surface fluctuations was observed on the downstream side, where a fully developed hydraulic jump was absent (Fig. 5b).

The absence of openings on the sidewalls (Configuration F, Fig. 5d) affected the flow around the building. The lack of water exchange through these openings resulted in flow depths significantly lower on both lateral sides. This flow behavior was similar to the fully impervious building ($P_{\text{tot}} = 0\%$) in Fig. 5a.

An orientation of the impervious building of $\theta = 45^\circ$ generated different streamline patterns compared to the impervious frontal configuration ($\theta = 0^\circ$, compare Fig. 5a with Fig. 6a) with a less pronounced horseshoe vortex, suggesting a better hydrodynamic performance of the configuration with $\theta = 45^\circ$. The flow remained symmetrical, leading to a stable V-shaped hydraulic jump originating directly at the downstream corner of the building. Conversely, an orientation with an angle $\theta = 22.5^\circ$ resulted in asymmetrical streamlines, generating a fluctuating V-shaped hydraulic jump (Fig. 6c).

For configurations with both an orientation and openings, the interactions between the main flow and the seepage flow resulted in flow patterns that were similar to those observed for the frontal permeable building (Fig. 6b and c). These were characterized by higher downstream flow depths and by the absence of a hydraulic jump, suggesting that the effect of building orientation was secondary to that of the openings, at least regarding the flow patterns.

On the upstream side of the building a local increase in flow depth was observed (Fig. 5c and d), attributed to the presence of bow waves.

As detailed in Fig. 1, the Ultrasonic-Distance Sensors (US) allowed to measure the flow depths both in the far upstream channel (h_1) and on the upstream side of the building (H). The ratios H/h_1 obtained for the largest tested discharge ($Q = 170$ l/s) are presented in Fig. 7 as a function of the upstream Froude number Fr_1 . Results for the frontal configuration showed ratios of ~ 1.07 – 1.10 , suggesting that vertical shelters should be designed with higher flow depths than those of the uniform flow condition. Data also revealed that for increasing porosities the ratios H/h_1 constantly decreased, confirming the benefit of openings in reducing the upstream flow depths, as compared to the impervious configuration. Nevertheless, configurations with openings revealed higher variability, as shown in Fig. 7 by the error bars representing the standard deviation of the measured flow depths. The rotation of the building, although increasing the blockage ratio, led for all configurations to a better hydrodynamic performance with reduced upstream flow depths, and thus safer vertical shelters.

6. Load analysis

The load exerted by the steady flow on all tested buildings is addressed herein and analyzed in terms of resistance coefficient C_R , total horizontal forces F_x , moment M_y and cantilever arm L_z . Note that transversal and vertical forces were not considered.

Fig. 5. Photos of the steady flow around the building ($\theta = 0^\circ$), (a) impervious building ($P_{\text{tot}} = 0\%$), (b) and (c) building configuration (O) with $P_{\text{tot}} = 17\%$, and (d) building configuration (F) with $P_{\text{tot}} = 17\%$ (see Fig. 3).

6.1. Impervious buildings with frontal and oriented exposures

First, the reference configuration (impervious $P_{\text{tot}} = 0\%$, $\theta = 0^\circ$) is considered, shown in Fig. 1. This configuration resulted in a blockage ratio $\beta = 0.21$ for which the contribution of the hydrostatic component to the total force was less relevant than the form drag (Qi et al., 2014). It was thus decided to include both components in a reference resistance coefficient $C_{R,0}$ (index 0 for reference impervious configuration, Eqs. (3) and (7)). A similar approach was presented by Gupta and Goyal (1975), Arnason et al. (2009) and Wüthrich et al. (2018c, b).

$$C_{R,0} = \frac{2F_x}{\rho B h_1 v_1^2} \quad (7)$$

where F_x is the average horizontal force, B the building width normal to the flow direction, h_1 the uniform flow depth and v_1 the uniform flow velocity, both measured far upstream of the building. The velocity v_1 was computed through continuity as $v_1 = Q/(h_1 \cdot W)$. Experimental values of the resistance coefficient $C_{R,0}$ for impervious ($P_{\text{tot}} = 0$, variable θ) buildings are shown as a function of the upstream Froude number Fr_1 in Fig. 8, indicating $C_{R,0} \approx 5$ to 6 for the present choked tests ($Fr_{1,c} \approx 0.43$). Even if these values are higher than those suggested by FEMA55 (2000), and ASCE 7–6 (2016), as well as by Blevins (1984) for pronounced subcritical flows, these are in agreement with those obtained by Qi et al. (2014) for similar choked flows and blockage ratios (Fig. 8).

A similar methodology was applied for buildings with an orientation ($\theta = 22.5^\circ$ and 45°), where only the total forces in the streamwise direction F_x were considered. This configuration resulted in a higher surface perpendicular to the flow and therefore slightly higher blockage ratios (Table 1). However, the resistance coefficients remained similar to

those of Qi et al. (2014), as shown in Fig. 8. Values obtained for the impervious building $C_{R,0}$ are used hereafter as a reference for the comparison to buildings with openings.

The force plate provided measurements of both forces and moments in time. An estimation of the application point of the resulting horizontal force F_x , i.e. the cantilever arm as vertical distance between the channel invert and the force application point L_z was obtained as (Fig. 1):

$$L_z = \frac{M_y}{F_x} \quad (8)$$

where F_x and M_y are the horizontal streamwise force and the moment around the transversal y -axis, time-averaged over $\Delta t = 60$ s. Experimental data revealed $L_z = 0.5 \cdot h_1$ for the configuration with frontal building ($\theta = 0^\circ$), consistent with the dynamic pressure distribution. For the configuration with an orientation, shorter cantilever arms were observed as compared to the frontal configuration (Fig. 9), confirming a better hydrodynamic performance in terms of moments acting on the structure. The normalized length of the cantilever arm L_z/h_1 , as a function of orientation θ , was best approximated by the empirical expression:

$$\frac{L_z}{h_1} = \frac{1}{2} - (0.12 \cdot \sin 2\theta) \quad (9)$$

6.2. Porous buildings with frontal exposures

For porous building with openings, the discharge through the building reduced the difference in flow depth between the upstream and the downstream sides and therefore the hydrostatic component. Data are plotted in Fig. 10, revealing a reduction of the resistance coefficient C_R

Fig. 6. Photos of steady flow around: (a) impervious building with $\theta = 45^\circ$; (b) configuration 0 with openings, $P_{\text{tot}} = 60\%$, $\theta = 45^\circ$ (c) impervious building with $\theta = 22.5^\circ$; (d) configurations with openings, $P_{\text{tot}} = 60\%$, $\theta = 22.5^\circ$. All pictures taken against flow direction.

Fig. 7. Flow depth H near the building (Fig. 1) compared to upstream uniform flow depth h_1 for configurations with openings and orientation. Values are for the maximum tested discharge ($Q = 170$ l/s). Error bars represent the value of the standard deviation.

[normalized with the reference resistance coefficients $C_{R,0}$ in Eq. (7)] as a function of porosity (i.e., the openings), here represented by the cumulative porosity P_h . The latter was defined at a height $h = h_1$, similarly to Wüthrich et al. (2018b). In Fig. 10, a strictly linear relationship of

$C_R/C_{R,0} = 1 - P_h$ provided a good estimation of the induced forces for all tested configurations. Note that all data are compared to the resistance coefficient $C_{R,0}$ obtained for the impervious reference configuration (Fig. 8). The authors attribute this force reduction to the presence of a

Fig. 8. Reference resistance coefficients $C_{R,0}$ as a function of the upstream Froude number Fr_1 for impervious ($P_{tot} = 0$) buildings with and without orientation. Current data is compared with Qi et al. (2014).

Fig. 9. Cantilever arm L_z (normalized with h_1) as a function of the building orientation θ and comparison with Eq. (9). Dotted line represents the symmetrical extension to $[45^\circ, 90^\circ]$.

flow through the building, responsible for higher flow depths on the downstream side and thus limiting the hydrostatic component of the force. This is supported by the visual observations in Fig. 5. Experiments also showed that even small openings ($P_{tot} = 17\%$) generated a substantial force reduction, suggesting that any seepage flow through the building could increase the downstream water level, minimizing the loading process on the building.

Configurations with openings in the front and back sides, but with impervious side-walls, were also tested (Configuration F, Fig. 3b). For steady subcritical flow conditions, lower resistance coefficients C_R (and

therefore horizontal forces F_x) were constantly recorded for all tested discharges and porosities for configuration F, as shown in Fig. 10 (empty symbols). This is in accordance with the visual observations presented above, showing lesser interaction between the main flow and the discharge through the openings on the side-walls (Fig. 5c and d). In addition, the absence of openings in the side-walls also reduced the total amount of surface perpendicular to the flow, on which the hydrodynamic force is applied. For the steady flow condition this reduction between configurations O and F represented approximately 20% of total horizontal force (i.e., C_R), for all tested scenarios and discharges. This is somehow in contrast with the unsteady flow condition, in which the sidewalls were shown to be uninfluential (Wüthrich et al., 2018b). This can be explained considering that in unsteady flows the maximum force is often associated with a more impulsive behavior, recorded before the post-peak hydrodynamic phase is established.

The absence of openings in the rear of the building (Configuration B, Fig. 3) generated only a small reduction of the resistance coefficient C_R (Fig. 8). Nevertheless, the loading conditions remained very similar to the reference impervious building (horizontal dotted line in Fig. 10). This is in agreement with unsteady flow conditions, showing that one impervious side perpendicular to the flow can remove all benefits of openings.

These results provided a modified expression of the resistance coefficient through the use of an empirical correction coefficient m , leading to a better agreement with experimental data (Fig. 8):

$$\frac{C_R}{C_{R,0}} = 1 - m \cdot P_h \quad (10)$$

where the experimental results gave: $m = 0$ for the fully impervious configurations and for the configurations with impervious back (Configuration B), $m = 1.0$ for the openings equally distributed on all sides (Configuration O in Fig. 3a) and $m = 1.2$ for the configurations with openings on front and back sides and impervious lateral sides (Configuration F). Eq. (10) also led to a modification of the porosity coefficient Π in Eq. (4) for the steady state conditions:

$$\Pi = 1 - m \cdot \min[(P_h)_{front}; (P_h)_{back}] \quad (11)$$

6.3. Porous buildings with oriented exposures

Shafiei et al. (2016) and Ylla Arbós et al. (2018) investigated the relation between building orientation (rotation around vertical axis) and the forces exerted by the flow on the building. Herein, the effect of openings on the oriented impervious buildings is addressed and discussed. Note that regardless of the orientation of the building, the total horizontal forces were measured in the flow direction (Fig. 1). Similarly, the frontal scenario, force measurements on oriented buildings showed lower values for buildings with openings, as compared to buildings without openings (Fig. 11). Note that in Fig. 11 every orientation was normalized with the corresponding impervious building ($C_{R,0}$) and that only the frontal porosity P_h ($\theta = 0^\circ$) was used. The agreement of all data indicated that the frontal porosity dominated, implying that the occurrence of seepage (regardless of its orientation) was a predominant factor in the determination of the resistance coefficient. Also, a higher influence on the resistance coefficient was observed for the configurations with larger openings in bottom part of the building ($P_{tot} = 31\%, 42\%$; Fig. 2), thus resulting in larger values of the cumulative porosity P_h .

7. Discussion

The present study provided a detailed investigation of the effect of building openings and orientation on the structural loading under steady flow conditions. This simulated the post-peak hydrodynamic phase during tsunamis or flood waves, responsible for damages to critical infrastructures. As such, these results represent an extension to steady

Fig. 10. Resistance coefficient C_R as a function of the cumulative porosity P_h for configurations 0 (all porous sides), F (impervious lateral walls), and B (impervious back side). Note that only buildings with $\theta = 0^\circ$ were considered herein. Data was normalized using the resistance coefficient for the impervious configuration $C_{R,0}$ (Eq. (7)).

Fig. 11. Effect of porosity P_h on C_R for buildings with an orientation θ . Note that all tested orientations are shown exclusively for the configuration 0 (openings equally distributed on all four sides). Data was normalized using the resistance coefficient for the corresponding impervious configuration $C_{R,0}$.

choked flows of the linear relationship between openings and forces previously reported for unsteady flows by Wüthrich et al. (2018b). However, these results can only be applied to subcritical flows with geometries, blockage ratios and flow conditions similar to those tested herein. It is believed that the disposition of the openings with a non-symmetrical arrangement with respect to the centerline might affect the loading process. Also, these results only take into account the effect of water, neglecting additional loads associated with air entrapped

in the flow, large debris and scour at the foundation of the structure. The current project was based on a Froude similitude in a large size facility, generating large Reynolds numbers that minimized scale effects. Given the limited presence of air in the upstream side of the building, the influence of the Weber number on the loading process was assumed to be minimal. Nevertheless the presence of scale effects might affect the upscaling of the drag coefficient and further studies are necessary to provide safe and reliable design guidelines.

8. Conclusions

The effect of building porosity and orientation (rotation) on the streamwise flow-induced force is investigated herein, for steady free-surface flows under a subcritical choked regime. The force is expressed in terms of the resistance coefficient C_R considering both hydrostatic and drag components. The following aspects resulted:

- For a frontal impervious building in a steady flow, the choked regime ($Fr_1 \sim Fr_{1c}$) induced a difference in flow depth between the upstream and the downstream side, generating a hydraulic jump downstream of the building.
- The recorded values of the resistance coefficients were consistent with previous experimental studies for a frontal flow affecting an impervious reference building. For the impervious frontal building the total horizontal forces were applied at a height equal to 50% of the flow depth.
- Results showed that a flow through the openings lowered the difference between the up- and down-stream flow depths, leading to lower horizontal forces. This strongly reduced the resistance coefficient, which was shown to be linearly related to the building porosity.
- In contrast to unsteady supercritical flows, the obstruction of the openings on the lateral sides of the building preventing any water exchange in the transversal direction, further reduced hydrodynamic forces by 20%, resulting in the introduction of an empirical coefficient $m = 1.2$ in Eqs. (10) and (11).
- Buildings with porous front and impervious back had almost similar load conditions to the impervious reference configuration.
- An orientation (rotation around the vertical axis) of the impervious building within the flow increased the blockage ratio, responsible for an increase in horizontal forces. However, these forces were applied at lower cantilever arms, thus reducing the tilting moments. Run-up heights upstream of the building were also lower for the configurations with orientation, thus generating safer vertical shelters.
- The influence of orientation became negligible for buildings with openings, suggesting that the effects induced by the seepage flow through the building were predominant in the definition of the resistance coefficient.

In practical applications, these results emphasize once more the key-role of openings in reducing the hydrodynamic loads exerted by the flow on the buildings and in limiting inundation depths, thus generating safer resilient structures.

CRedit authorship contribution statement

Davide Wüthrich: Conceptualization, Data curation, Formal analysis, Writing - original draft. **Michael Pfister:** Conceptualization, Funding acquisition, Supervision, Writing - review & editing. **Anton J. Schleiss:** Funding acquisition, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Arason, H., 2005. Interactions between an Incident Bore and a Free-Standing Coastal structure. *PhD Thesis*. University of Washington, Seattle, USA, p. 172.
- Arason, H., Petroff, C., Yeh, H., 2009. Tsunami bore impingement onto a vertical column. *J. Disaster Res.* 4 (6), 391–403.
- Asadollahi, N., Nistor, I., Mohammadian, A., 2019a. Numerical investigation of tsunami bore effects on structures, part I: drag coefficients. *Nat. Hazards* 96 (1), 285–309.
- Asadollahi, N., Nistor, I., Mohammadian, A., 2019b. Numerical investigation of tsunami bore effects on structures, part II: effects of bed condition on loading onto circular structures. *Nat. Hazards* 96 (1), 331–351.
- ASCE7-6 Structural Engineering Institute, 2016. Minimum Design Loads for Buildings and Other Structures. ASCE/SEI 7-16. Reston, VA.
- Benjamin, T.B., 1956. On the flow in channels when rigid obstacles are placed in the stream. *J. Fluid Mech.* 1 (2), 227–248.
- Blevins, R.D., 1984. Applied Fluid Dynamics Handbook. Van Nostrand Reinhold Co., New York, USA, p. 568.
- Chanson, H., 2006. Tsunami surges on dry coastal plains: application of dam break wave equations. *Coast. Eng.* 48 (4), 355–370.
- Chaplin, J.R., Teigen, P., 2003. Steady flow past a vertical surface-piercing circular cylinder. *J. Fluid Struct.* 18, 271–285.
- Chock, G., Robertson, I., Kriebel, D., Francis, M., Nistor, I., 2012. Tohoku Japan Tsunami of March 11, 2011: Performance of Structures. *American Society of Civil Engineers (ASCE)*, p. 348.
- Cox, D., Tomita, T., Lynett, P., Holman, R., 2008. Tsunami inundation with macro-roughness in the constructed environment. *Coast. Eng.* 1421–1432.
- Cuomo, G., Shams, G., Jonkman, S., Van Gelder, P., 2009. Hydrodynamic loadings of buildings in floods. *Coast. Eng.* 3744–3756, 2008.
- Dargahi, B., 1989. The turbulent flow field around a circular cylinder. *Exp. Fluids* 8 (1–2), 1–12.
- Dias, P., Dissanayake, R., Chandratilake, R., 2006. Lessons learned from tsunami damage in Sri-Lanka. *Proc. Inst. Civ. Eng.* 159 (2), 74–81.
- Faisal, N.A.A., Ghani, A.N.A., Salim, N.A.A., 2018. The ability of wall openings to reduce flood induced forces on residential buildings. *Int. J. GEOMATE* 14 (46), 63–69.
- Fema55, 2000. Coastal Construction Manual. Federal Emergency Management Agency (FEMA), DC, USA, p. 82 (Chapter 8) - Washington.
- Fenton, J.D., 2003. The effects of obstacles on surface levels and boundary resistance in open channels. In: *Proceedings of the 30th IAHR World Congress*, pp. 9–16. C2 (Thessaloniki, Greece, 24–29 August).
- Fenton, J.D., 2008. Obstacles in streams and their roles as hydraulic structures. In: *Hydraulic Structures – Proceedings of the 2nd International Junior Researcher and Engineer Workshop on Hydraulic Structures*. Pisa, Italy, 30 July–1 August.
- Foster, A.S.J., Rossetto, T., Allsop, W., 2017. An experimentally validated approach for evaluating tsunami inundation forces on rectangular buildings. *Coast. Eng.* 128, 44–57.
- Fritz, H.M., Phillips, D.A., Okayasu, A., Shimozono, T., Liu, H., Mohammed, F., Skanavis, V., Synolakis, C.E., Takahashi, T., 2012. The 2011 Japan tsunami current velocity measurements from survivor videos at Kesennuma bay using Lidar. *Geophys. Res. Lett.* 39, 1–6.
- Ghodoosipour, B., Stolle, J., Nistor, I., Mohammadian, A., Goseberg, N., 2019. Experimental study on extreme hydrodynamic loading on pipelines part 2: induced force analysis. *J. Mar. Sci. Eng.* 7 (8), 262.
- Goseberg, N., 2013. Reduction of maximum tsunami run-up due to the interaction with beachfront development—application of single sinusoidal waves. *Nat. Hazards Earth Syst. Sci.* 13 (11), 2991–3010.
- Goseberg, N., Schlurmann, T., 2014. Non-stationary flow around buildings during run-up of tsunami waves on a plain beach. In: *Proceedings of the Coastal Engineering Conference*. June, Seoul, Korea, pp. 15–20.
- Goseberg, N., Wurpts, A., Schlurmann, T., 2013. Laboratory-scale generation of tsunami and long waves. *Coast. Eng.* 79, 57–74.
- Gupta, V.P., Goyal, S.C., 1975. Hydrodynamic forces on bridge piers. *J. Inst. Eng. (India) Civ. Eng. Div.* 56, 12–16.
- Henderson, F.M., 1966. Open Channel Flow. MacMillan Company, New York, USA, p. 522.
- Jaffe, B.E., Goto, G., Sugawara, D., Richmond, B.M., Fujino, S., Nishimura, Y., 2012. Flow speed estimated by inverse modeling of sandy tsunami deposits: results from the 11 March 2011 tsunami on the coastal plain near the Sendai Airport, Honshu, Japan. *Sediment. Geol.* 282, 90–109. <https://doi.org/10.1016/j.sedgeo.2012.09.002>.
- Jansen, L., Korswagen, P.A., Bricker, J.D., Pasterkamp, S., de Bruijn, K.M., Jonkman, S. N., 2020. Experimental determination of pressure coefficients for flood loading of walls of Dutch terraced houses. *Eng. Struct.* 216, 110647.
- Mignot, E., Riviere, N., 2010. Bow-wave-like hydraulic jump and horseshoe vortex around an obstacle in a supercritical open channel flow. *Phys. Fluids* 22 (11), 117105.
- Mignot, E., Moyné, T., Doppler, D., Riviere, N., 2016. Clear-water scouring process in a flow in supercritical regime. *J. Hydraul. Eng.* 142 (4), 04015063.
- Mikami, T., Shibayama, T., Esteban, M., Takabatake, T., Nakamura, R., Nishida, Y., Achiari, H., Marzuki, A.G., Marzuki, M.F.H., Stolle, J., Krautwald, C., 2019. Field survey of the 2018 Sulawesi tsunami: inundation and run-up heights and damage to coastal communities. *Pure Appl. Geophys.* 176 (8), 3291–3304.
- Moon, W.C., Lau, T.L., Puay, H.T., 2020. Experimental investigations of tsunami loading on internal wall of a building with various openings and wall configurations. *Coast. Eng.* 158, 103691.
- Nagler, F.A., 1918. Obstruction of bridge piers to the flow of water. *Proc. Am. Soc. Civ. Eng.* 43 (5), 815–846.

- Nouri, Y., Nistor, I., Palermo, D., Cornett, A., 2010. Experimental investigation of tsunami impact on free standing structures. *Coast Eng. J.* 52 (1), 43–70. <https://doi.org/10.1142/S0578563410002117>.
- Park, H., Cox, T., Lynett, P.J., Wiebe, D.M., Shin, S., 2013. Tsunami inundation modeling in constructed environments: a physical and numerical comparison of free-surface elevation, velocity, and momentum flux. *Coast. Eng.* 79, 9–21.
- Qi, Z.X., Eames, I., Johnson, E.R., 2014. Force acting on a square cylinder fixed in a free-surface channel flow. *J. Fluid Mech.* 756, 716–727.
- Raju, K.G.R., Rana, O.P.S., Asawa, G.L., Pillai, A.S.N., 1983. Rational assessment of blockage effect in channel flow past smooth circular cylinders. *J. Hydraul. Res.* 21 (4), 289–302.
- Riviere, N., Vouaillat, G., Launay, G., Mignot, E., 2017. Emerging obstacles in supercritical open-channel flows: detached hydraulic jump versus wall-jet-like bow wave. *J. Hydraul. Eng.* 143 (7), 04017011.
- Roeber, V., Bricker, J.D., 2015. Destructive tsunami-like wave generated by surf beat over a coral reef during typhoon Haiyan. *Nat. Commun.* 6, 7854.
- Shafiei, S., Melville, B.W., Shamseldin, A.Y., 2016. Experimental investigation of tsunami bore impact force and pressure on a square prism. *Coast. Eng.* 110, 1–16.
- Wüthrich, D., 2018. Extreme Hydrodynamic Impact onto Buildings. PhD thesis. LCH/EPFL, Lausanne, Switzerland, p. 246 (No. 8116) and Communication LCH 74.
- Wüthrich, D., Pfister, M., Nistor, I., Schleiss, A.J., 2018a. Experimental study of tsunami-like waves on dry and wet bed generated with a vertical release technique. *J. Waterw. Port. Coast. Ocean Eng.* 144 (4), 04018006.
- Wüthrich, D., Pfister, M., Nistor, I., Schleiss, A.J., 2018b. Experimental study on forces exerted on buildings with openings due to extreme hydrodynamic events. *Coast. Eng.* 140, 72–86.
- Wüthrich, D., Pfister, M., Nistor, I., Schleiss, A.J., 2018c. Experimental study on the hydrodynamic impact of tsunami-like waves against impervious free-standing buildings. *Coast Eng. J.* 60 (2), 180–199.
- Xiong, Y., Liang, Q., Park, H., Cox, D., Wang, G., 2019. A deterministic approach for assessing tsunami-induced building damage through quantification of hydrodynamic forces. *Coast. Eng.* 144, 1–14.
- Yarnell, D.L., 1934. Bridge piers as channel obstructions. In: Technical Bulletin, 442. Department of Agriculture, USA, p. 80.
- Yeh, H., 2006. Maximum fluid forces in the tsunami run-up zone. *J. Waterw. Port. Coast. Ocean Eng.* 132 (6), 496–500.
- Ylla Arbós, C., Wüthrich, D., Pfister, M., Schleiss, A.J., 2018. Wave impact on oriented impervious buildings. In: *Proceedings of the 5th IAHR Europe Congress*. June, Trento, Italy, pp. 12–14.
- Zhou, Q., Yu, W., Chen, A.S., Jiang, C., Fu, G., 2016. Experimental assessment of building blockage effects in a simplified urban district. *Procedia Eng.* 154, 844–852.