

Numerical Analysis of Tsunami Bore–Induced Forces on Structures: Evaluating the Mitigation Potential of a Water-Filled Canal

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Abstract

Although tsunamis are unpredictable natural events, their impact on coastal areas can be mitigated through the implementation of effective countermeasures. Both engineered and nature-based strategies have been employed to dissipate tsunami energy to protect infrastructure near affected coastlines and safeguard human life. Among these countermeasures, water-filled canals have proven to be effective in reducing tsunami energy, as demonstrated through field investigations, experimental studies, and numerical analyses. The interaction of tsunami bores with water-filled canals and their subsequent impact on structures is a complex phenomenon that requires a detailed investigation. Understanding the flow hydrodynamics around the canal and structure, pressure distribution, and force-time history on structures is essential for optimizing such mitigation strategies. In this study, a series of calibrated numerical simulations were conducted using a prototype-scale model to investigate the effectiveness of various dimensions of water-filled canal to reduce the horizontal force exerted on a downstream column. FLOW-3D was selected as the modeling tool due to its robustness and demonstrated capability to simulate complex fluid-structure interactions. The reduction factor for a specific tsunami bore characteristic depends on the geometry of the canal. In this study, for a tsunami-like bore generated by a 4 m-deep dam-break flow, the reduction factor reached up to approximately 40% for a canal with a depth of 4.5 m and a width of 40 m. The results showed that the presence of the canal had a much greater effect on reducing the tsunami-like bore-induced force on the column during the initial impact. The results also indicate that there is a threshold for both canal width and depth, beyond which further increases do not significantly enhance force reduction on the column. Moreover, the effect of canal width on increasing the reduction factor is considerably greater than that of canal depth. These findings suggest that, in designing a canal as a tsunami mitigation countermeasure, both the absolute dimensions and the ratio of width to depth should be carefully considered.

Highlights:

- Investigated the effectiveness of rectangular water-filled canals in mitigating tsunami-like bore forces on columns.

- 46 • Calibrated FLOW-3D numerical simulations were used alongside experimental data for validation.
- 47 • Developed real-scale models to eliminate scaling effects and better represent tsunami dynamics.
- 48 • Found that canal width had a greater impact than depth, achieving up to 40% force reduction.
- 49 • Provides practical design insights for future coastal protection using water-filled canals.

50

51 **Keywords:** Tsunami-like bore, tsunami mitigation countermeasures, water-filled canal, horizontal force,
52 numerical modeling, FLOW-3D

53

1. Introduction

Tsunamis are complex natural phenomena that are typically generated when a large volume of water suddenly moves, creating a long wave. These waves can travel across the entire ocean at high speeds, grow in height as they approach shallow coastal waters, and may eventually break into several bores, often causing catastrophic damage to infrastructure, ecosystems, and communities (Bryant, 2014). Tsunamis, though rare, represent a profound hazard to coastal zones, often resulting in widespread devastation and significant loss of life (Nistor et al., 2009).

As tsunamis occur rarely, it is difficult to perform field experiments. Therefore, most studies on how tsunamis propagate and interact with structures located in coastal areas have relied on laboratory experiments and numerical simulations (Wei et al., 2015). While significant advancements have been made in understanding and modeling tsunamis, challenges remain in predicting their occurrence and mitigating their effects, particularly in densely populated coastal regions. Understanding these dynamics is crucial for enhancing disaster resilience and response strategies (Synolakis & Bernard, 2006).

Field surveys of recent tsunami events, such as the 2004 Indian Ocean Tsunami (Heidarzadeh et al., 2020), 2011 Tohoku Tsunami (Chock et al., 2013), 2018 Indonesia Tsunami (Syamsidik et al., 2019), and 2024 Noto Tsunami (Inagaki et al., 2025), have highlighted the urgent need for effective disaster mitigation strategies to protect coastal communities and infrastructure. The implementation of comprehensive risk-reduction measures can significantly reduce the impact of tsunamis, as evidenced by various methodologies and technologies developed in recent research. To mitigate tsunami-induced effects on infrastructure, various design provisions and planning measures have been developed that focus on both natural and man-made solutions (Suppasri et al., 2013; Oetjen et al., 2022).

Hard engineering solutions, such as sea walls, breakwaters, and offshore barriers, provide physical protection by deflecting or dissipating the force of incoming tsunami waves. However, they are often expensive to construct and maintain (Synolakis & Bernard, 2006). In contrast, soft engineering approaches such as mangrove plantations, dune restoration, and wetland rehabilitation enhance coastal resilience

79 through natural processes, offering sustainable and cost-effective defense while benefiting local
80 ecosystems, although they typically provide less robust protection during extreme events and require time
81 to establish (Alongi, 2008). Among these, water-filled canals have emerged as a particularly effective
82 solution for reducing tsunami energy. Their effectiveness has been validated through field investigations,
83 experimental studies, and numerical modeling, highlighting their potential as reliable mitigation measures
84 for coastal protection strategies (Rahman et al., 2017; Elsheikh et al., 2020).

85 Canals aligned parallel to coastlines have been shown to effectively dissipate tsunami energy, thereby
86 reducing the impact of coastal inundation. A prominent example is the Buckingham Canal, located along
87 the Chennai coastline, which measures approximately 30 m wide and 10 m deep. During the 2004 Indian
88 Ocean tsunami, it significantly reduced the energy of the incoming bore and played a vital role in saving
89 lives (Rahman et al., 2017). The Buckingham Canal's role during the 2004 tsunami exemplifies the life-
90 saving potential of these measures (Elsheikh et al., 2020). Similarly, field investigations of the 49 km Kita-
91 Teizan Canal revealed its effectiveness in mitigating damage during the 2011 Japan tsunami by reducing
92 bore velocity and the resulting forces on downstream infrastructure. While these findings underline the
93 critical role of water-filled canals in tsunami impact mitigation, their effectiveness is highly dependent on
94 factors, such as canal design, location, and local geographic conditions. This emphasizes the need for further
95 research on the interaction of tsunami bores with water-filled canals and the dynamics of force transmission
96 to structures located downstream. Understanding these interactions will aid in optimizing canal designs to
97 maximize energy dissipation and enhance infrastructure protection.

98 Water-filled canals can significantly mitigate tsunami energy and reduce the force exerted on
99 downstream structures by reducing the tsunami inundation velocity (Rahman et al., 2017). The interaction
100 of tsunami waves with canals creates turbulence, which dissipates energy and reduces the impact on
101 downstream structures (Arefi et al., 2025).

102 Although experimental tests offer valuable insights into tsunami-induced hydrodynamics, they often
103 have notable limitations that necessitate the use of numerical modeling. Laboratory experiments typically

rely on scaled-down physical models. In addition, physical modeling is both costly and resource-intensive, often requiring extensive setup, instrumentation, and specialized facilities. Given these constraints, numerical modeling offers a practical and efficient alternative. This allows for high-resolution analysis of fluid dynamics over complex geometries and extended domains. In this study, FLOW-3D was employed for its capability to simulate transient free-surface flows and fluid-structure interactions which make it well suited for this study. The numerical model was calibrated using experimental data. To capture the detailed interactions between the tsunami bore, the canal, and the structure, the simulations were conducted at real scale. Various dimensions of the water-filled canal were considered to investigate their effects on reducing the force exerted on a column located behind the canal. Key parameters examined include flow depth along the tsunami path, velocity patterns around the canal and column, and the time history of the force acting on the column. These analyses aim to provide a better understanding of the canal's effectiveness as a tsunami mitigation countermeasure.

1.1. Objectives and novelty

This study aims to investigate the effectiveness of water-filled canals as a mitigation strategy for reducing tsunami-induced forces on structures located in coastal areas. While previous research has explored various countermeasures, the role of water-filled canals has not been fully evaluated in terms of their hydrodynamic behavior and energy dissipation performance under tsunami-like bore impacts. To address this gap, a series of calibrated numerical simulations was conducted using FLOW-3D software. These simulations were designed at the prototype scale to analyze how different canal configurations influence wave transformation, flow patterns, and the resulting forces exerted on downstream structures.

The primary objectives of this study were as follows:

- i) To investigate the effectiveness of a rectangular water-filled canal in reducing tsunami bore forces on a column.

- ii) To use calibrated numerical modeling for a deeper understanding of the interactions between tsunami-like bores, water-filled canals, and structures.
- iii) To apply real-scale numerical simulations to eliminate scaling effects and obtain a more realistic representation of tsunami behavior.
- iv) To conduct a detailed assessment of how canal geometry (width and depth) influences force reduction, turbulence, and flow dynamics.

2. Experimental Setup

To calibrate the numerical modeling, a series of experimental tests were performed at the Water Resources Engineering Laboratory of the University of Ottawa, Canada, using a tilting flume with 15.60 m in length, 0.38 m in width, and 0.60 m in depth. Figure 1 illustrates the side and plan views of the experimental setup.

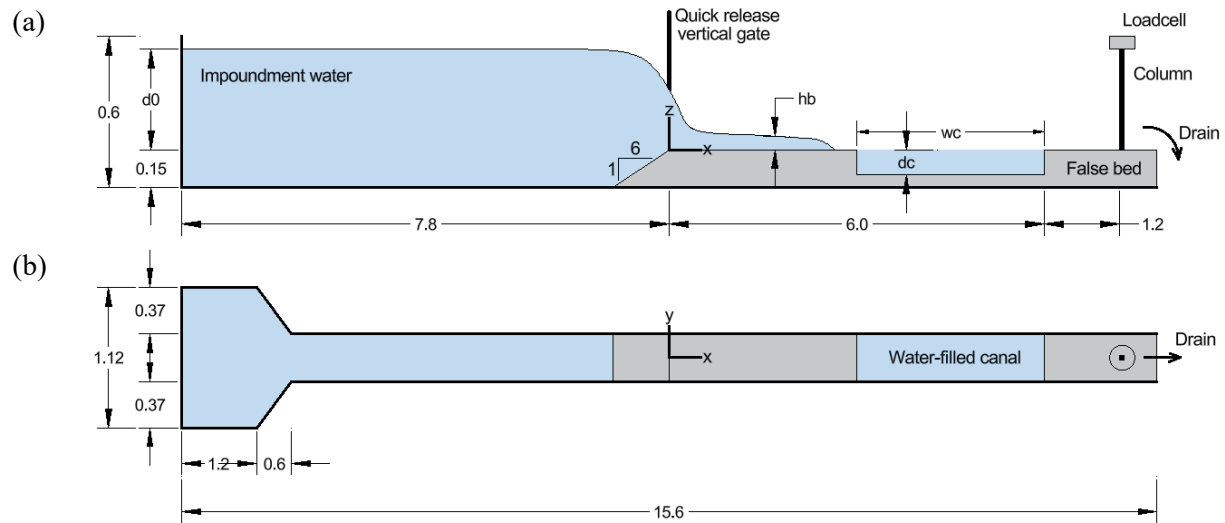


Figure 1. Schematic of the experimental setup (a) side, and (b) plan view (all dimensions in m)

Various canal configurations were tested, featuring depths of 5, 10, and 15 cm and widths of 60, 160, and 300 cm, by replacing the boxes installed on the bed of the flume. A 1:6 sloped bed was installed upstream of the gate to mitigate the local turbulence at the front of the false bed. A 4 cm square column was positioned at the end of the flume.

Tsunami-like bores were generated by rapidly lifting the gate was positioned at 7.8 m upstream end of the reservoir ($x=0$). The reservoir filled to predetermined water levels of 20, 30, and 40 cm above the false bed, corresponding to water impoundment volumes of 0.805, 1.208, and 1.611 m³, respectively. As illustrated in Figure 1, the reservoir is wider in the upstream area to accommodate a larger water volume in a limited flume length. To determine the aspect ratio of the reservoir length to water impoundment depth (L_{eq}/d_0), the equivalent length was calculated as $L_{eq}=10.6$ m. For impoundment water depths (d_0) of 20, 30, and 40 cm, the equivalent aspect ratios (L_{eq}/d_0) were calculated to be 53, 35.3, and 26.6, respectively. These values significantly exceed the recommendations of Lauber and Hager (1998) for generating an ideal tsunami bore, highlighting the unique experimental conditions of this setup.

The generated tsunami-like bore propagated along the flume, crossed over the canal, and after impacting the column, was dropped through a vertical drain at the end of the flume. Four ultrasonic distance sensors were placed at certain locations along the flume to monitor the bore depth variations. Additionally, a 6-axial load cell mounted on top of the column recorded the time history of the bore induced forces exerted on the column. Five GoPro Hero5 video cameras were employed to monitor the propagation of the bore along the flume, its behavior before and after entering the canal, and around the column. Further details of the experiments can be found in Arefi et al. (2025).

3. Numerical Modeling

For decades, numerical models have been employed to address complex engineering problems. Due to the rapid development of computers and their power of calculation, the use of numerical models is increasing every day. In this study, to analyze the effects of water-filled canals to reduce tsunami-like bore induced forces on a structure located behind the canal, a series of numerical modeling was performed using FLOW-3D. This software was selected because of its robustness in simulating coastal engineering problems (Alemi and Maia, 2018; April-Le Quéré et al., 2022; Yang et al., 2025) and has been applied by many researchers to study hydrodynamic forces on structures (Thanyamanta et al., 2011; Ghasemi et al., 2023).

3.1. Governing equations

FLOW-3D solves the Navier-Stokes momentum equations in all directions, allowing a fully nonhydrostatic solution methodology for the flow. The continuity and momentum equations, which are solved in all Cartesian directions, are expressed as

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\nu) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + F_i \quad (2)$$

where u_i and u_j are the velocity vectors, t is the time, x_i and x_j are the position vectors, P is the pressure, ρ is the fluid density, ν is the eddy viscosity, and F_i represents the external force.

Using the fractional area/volume method (FAVOR), FLOW-3D is capable of modeling complex geometric regions within a rectangular grid. To ensure simulation stability and convergence, an automatic time-step adjustment mechanism was implemented (Yang et al., 2025). In addition, sharp free surfaces can be captured using the Volume of Fluid (VOF) method.

3.2. Numerical setup

The computational domain was considered the same as in the experimental setup. The false floor and column were created by introducing boxes with dimensions like those used in the experiments. All boundaries were defined as zero gradient pressure boundaries except the downstream boundary, where a constant pressure boundary ($z=-10$ m) was applied, allowing the water to exit the numerical domain with no reflection and changes in the water level during the simulation. The mesh design employs a graded approach with varying cell sizes to ensure both computational efficiency and accuracy, which is achieved by using different mesh blocks throughout the computational domain (Figure 2). The finest mesh was utilized in the vicinity of the column to capture the detailed flow interactions and hydrodynamic forces accurately.

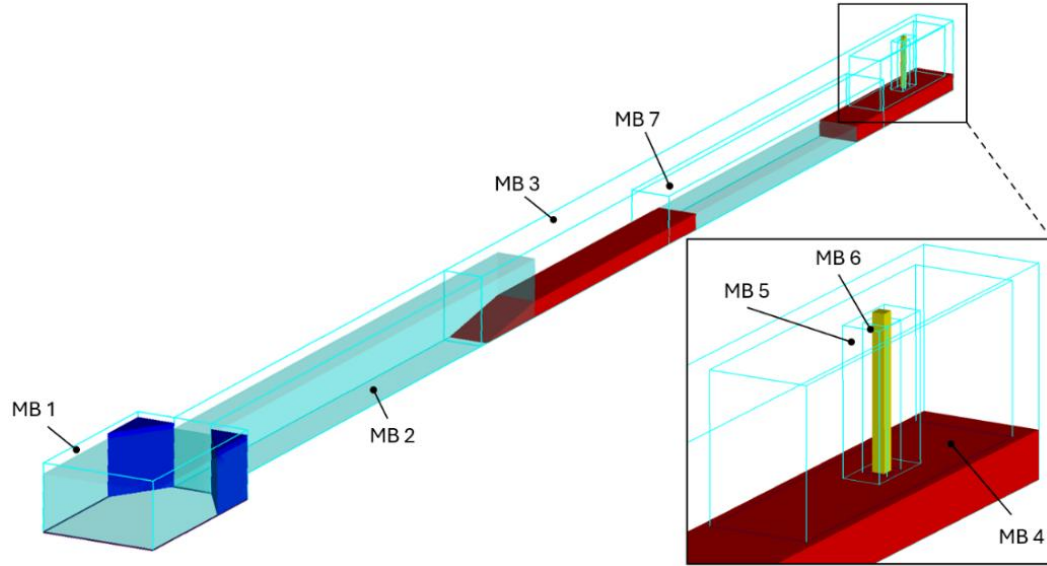


Figure 2: Mesh design based on experimental tests

Table 1: The positions of each mesh block in the x , y , and z directions and relative mesh size

Mesh Block	Region	Extent of mesh blocks						Mesh size (-)
		<i>x</i> -direction (m)		<i>y</i> -direction (m)		<i>z</i> -direction (m)		
MB1	Reservoir	-7.8	-6.04	-0.56	0.56	-0.15	0.5	6M*
MB2	Upstream flume	-6.04	-1	-0.19	0.19	-0.15	0.5	5M
MB3	Downstream flume	-1	7.8	-0.19	0.19	-0.15	0.5	3M
MB4	Around column (1)	6.5	7.7	-0.16	0.16	0	0.47	M
MB5	Around column (2)	7.1	7.34	-0.06	0.06	0	0.46	0.6M
MB6	Around column (3)	7.18	7.26	-0.04	0.04	0	0.45	0.25M
MB7	Around canal	2.5	6.5	-0.19	0.19	-0.15	0.3	M

* M is the mesh size of MB4 and MB7 which will be determined based on mesh sensitivity analysis

3.3. Mesh sensitivity analysis

Mesh sensitivity analyses are essential for balancing the accuracy and efficiency of numerical modeling. In this study, four different models were tested using 2,350,000 ($M=0.5$ cm), 1,200,000 ($M=1$ cm), 550,000 ($M=1.3$ cm), and 150,000 ($M=2$ cm) meshes. Figure 3 presents the time history of the horizontal force exerted on the column for a test without a canal and with a water impoundment depth of 40 cm. In all models, a square column (4 cm $\times$ 4 cm) was placed at $x=720$ cm. Based on the results, the model with 1,200,000 cells ($M = 1$ cm) was selected, as it provided reliable accuracy while maintaining

computational efficiency. As illustrated in Figure 3, further increasing the number of mesh elements did not lead to a significant improvement in the results.

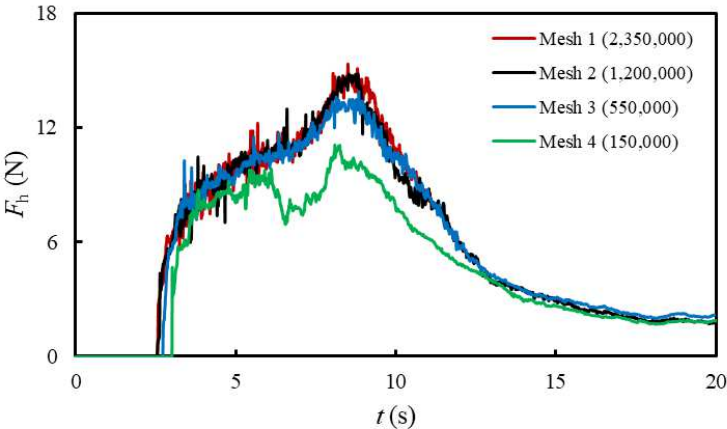


Figure 3: Mesh sensitivity analysis for four different models (the value in the parenthesis indicates the number of mesh cells)

3.4. Turbulence model

The turbulence model is essential for simulating the turbulent regime caused by the interaction of a tsunami-like bore with a water-filled canal and column. After evaluating four turbulence models of $k-\varepsilon$, RNG, $k-\omega$, and Smagorinsky, available in FLOW-3D, based on the time histories of bore depth and horizontal force on the column, the Smagorinsky model was selected, as it provided the best results compared with experimental data despite computational limitations in resolving boundary layer. Figure 4 and Figure 5 show a comparison of the water surface profiles resulting from these interactions for both the numerical simulations and experimental tests at different time steps. As shown in these figures, the numerical model reasonably captures the essential details of this complex flow regime.

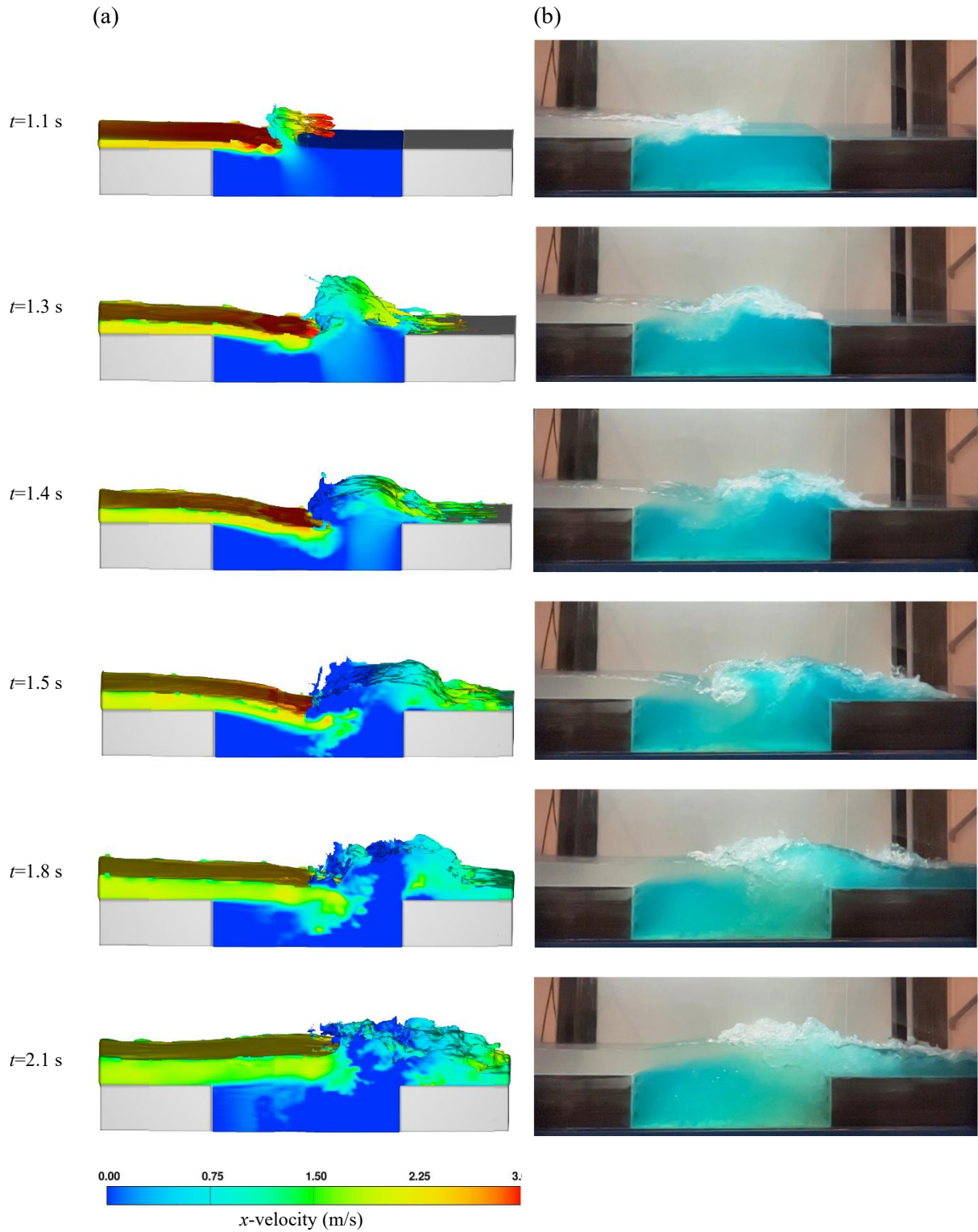


Figure 4: Tsunami-like bore interaction with water-filled canal at different time steps for (a) numerical modeling with x -velocity pattern, and (b) experimental test ($d_0=40$ cm, $w_c=60$ cm, $d_c=15$ cm)

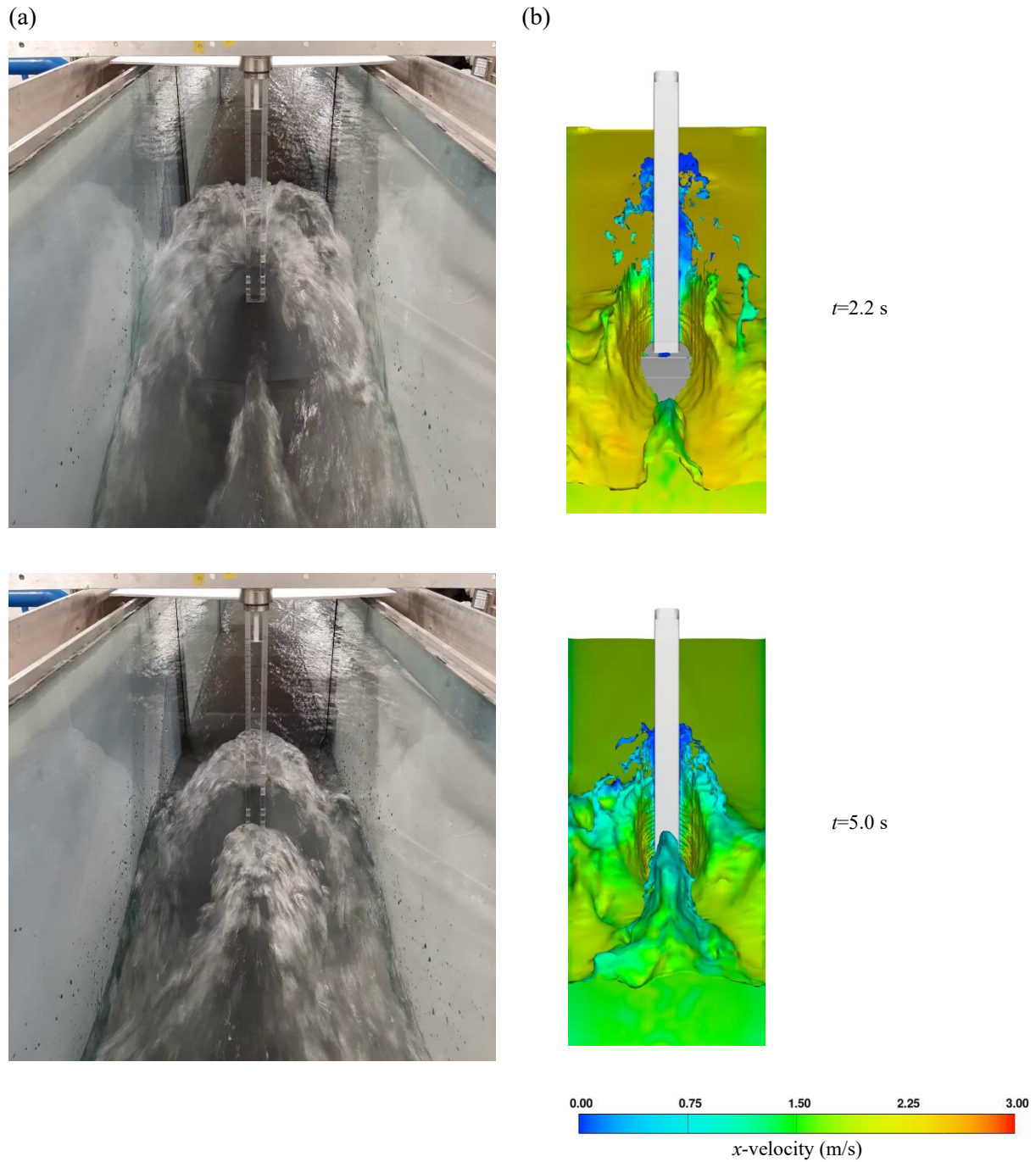


Figure 5: Bore interaction with column at different time steps for (a) experimental test, and (b) numerical modeling (Test without canal, $d_0=40$ cm, and the column is located at $x=720$ cm)

3.5. Validation

Figure 6 and

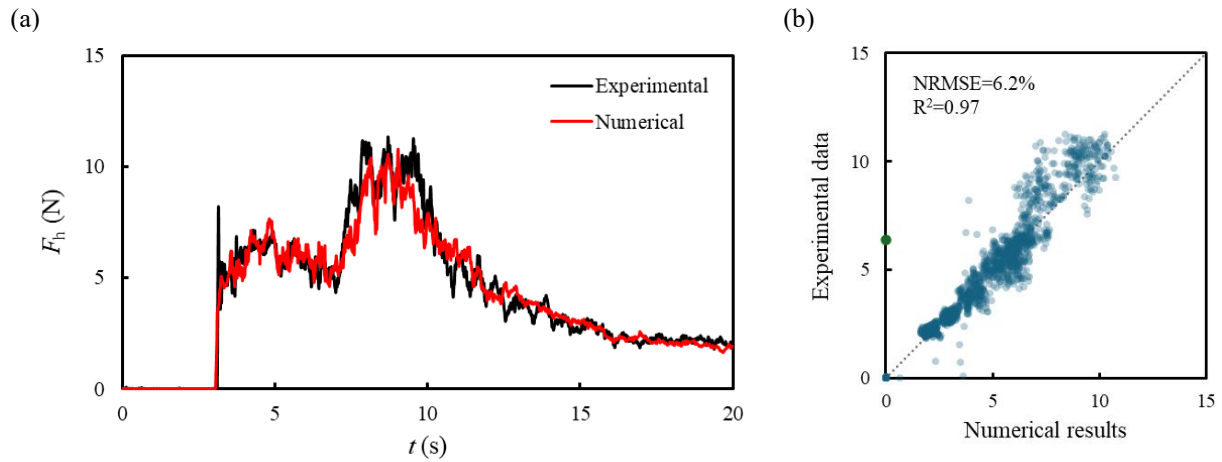


Figure 7 present the comparisons of time histories of the horizontal force for two test scenarios: a test without a canal where the column was located at $x=420$ cm (Without canal-With column), and a test involving a canal 300 cm wide and 15 cm deep, with the column positioned at $x=660$ cm (With canal-With column). In both cases, a 40 cm deep impoundment was considered upstream of the gate. The results demonstrate good agreement between the numerical and experimental data, with NRMSE of 5.6 and 6.2%. Additionally, bore depth comparisons are shown in Figure 8 and Figure 9 for a test without a canal and column (Without canal-Without column), and a test with a 60 cm wide, 15 cm deep canal and no column (With canal-Without column). NRMSE for these comparisons were 2.9 and 7.2%, further confirming the accuracy of the model.

In summary, the numerical model demonstrated a good agreement with the experimental data across multiple configurations. This level of accuracy was achieved without parameter tuning, relying only on the use of a sufficiently refined mesh to capture complex hydrodynamic behavior. This successful validation provides a solid foundation for using the model to explore additional scenarios and assess the effectiveness of water-filled canals as a tsunami force mitigation countermeasure.

(a)

(b)

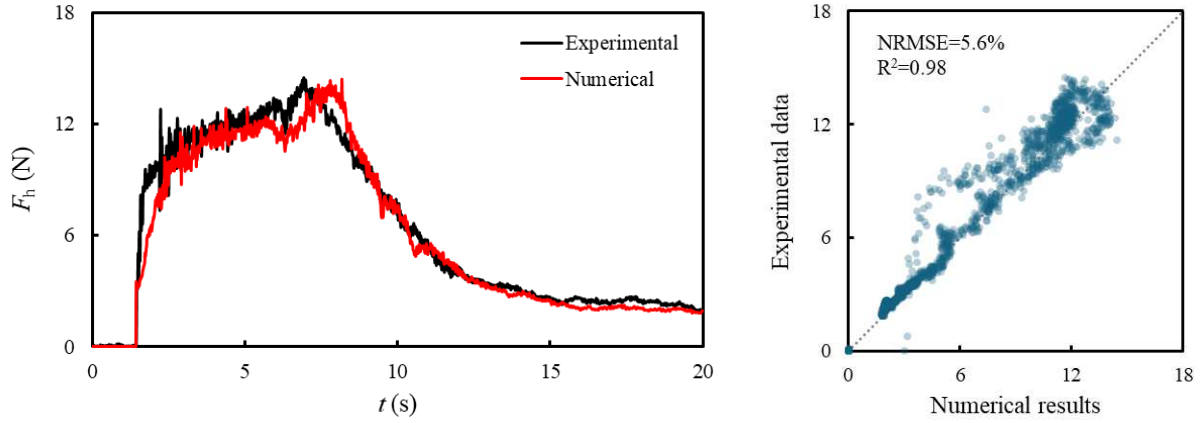


Figure 6: (a) Comparison of horizontal force on column for numerical modeling results and experimental data, and (b) scatter plot and NRMSE for the test Without canal-With column

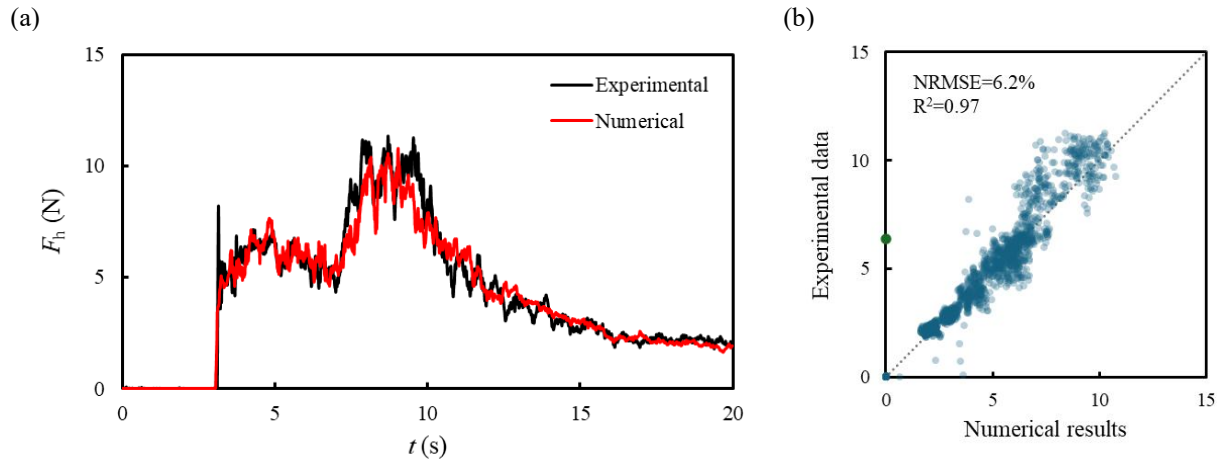


Figure 7: (a) Comparison of horizontal force on column for numerical modeling results and experimental data, and (b) scatter plot and NRMSE for the test With canal-With column

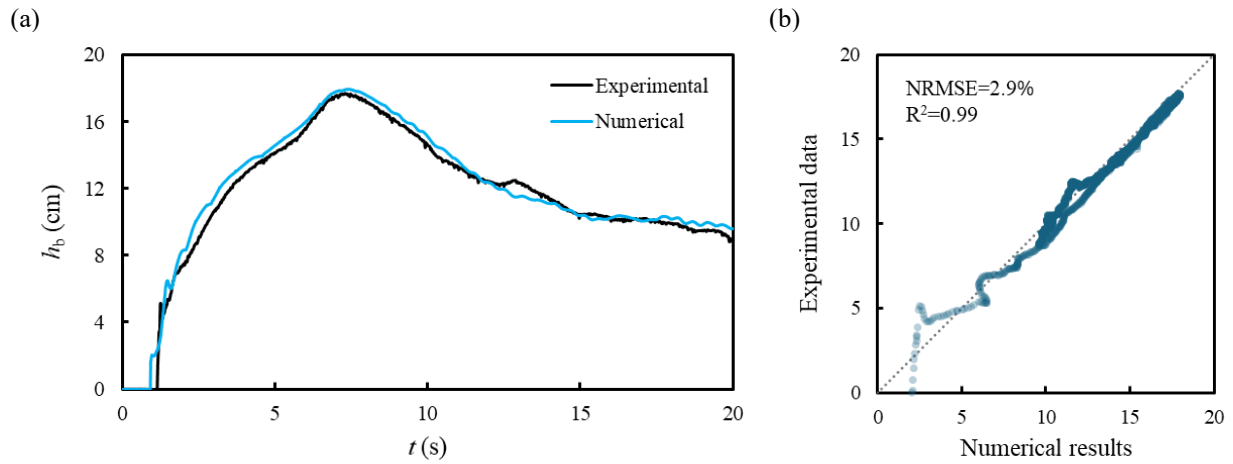


Figure 8: (a) Comparison of bore depth at $x=2.7$ m for numerical modeling results and experimental data, and (b) scatter plot and NRMSE for the test Without canal-Without column

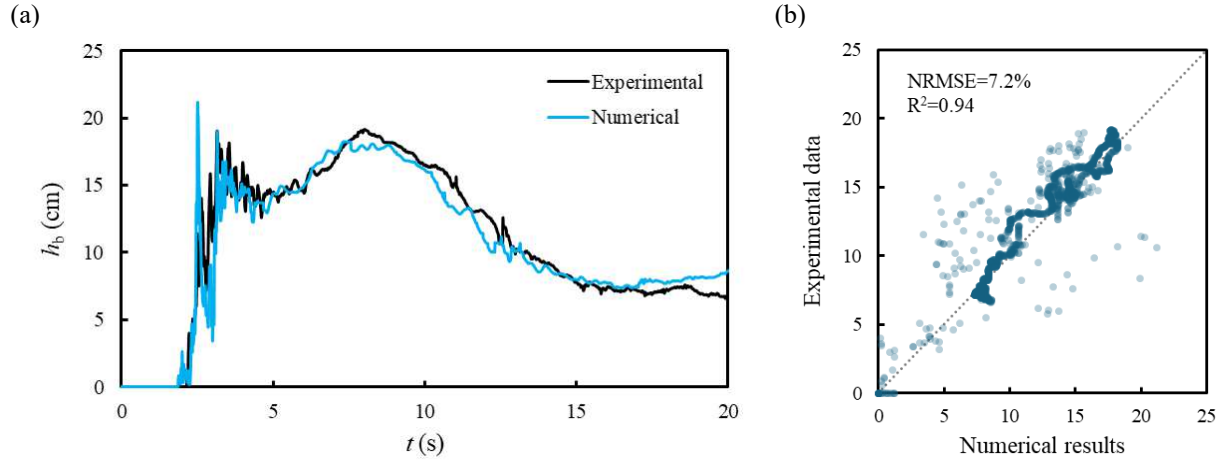


Figure 9: (a) Comparison of bore depth at $x=3.9$ m for numerical modeling results and experimental data, and (b) scatter plot and NRMSE for the test With canal-Without column

4. Flume limitations in experimental tests

4.1. Scale effect

Unlike physical experiments constrained by laboratory size, numerical models can be conducted without spatial or temporal limitations. While small-scale models provide valuable insights into complex phenomena, scaling down introduces distortions in the dynamic and flow parameters that are challenging to replicate accurately.

The physical experiments in this study, conducted at a 1:10 Froude scale, highlighted phenomena that may not scale perfectly. These discrepancies can result in variations in the flow dynamics and force measurements when extrapolated to full scale. By employing 1:1 numerical modeling, these scale effects are inherently avoided, ensuring a more accurate representation of the true physical behavior. In this regard, the results of numerical simulations conducted at the experimental scale (1:10) with those at the prototype scale (1:1) were compared. In both cases, the water impoundment depth was set to 4 m, and the column was positioned at $x=72$ m, and in the scenario with canal, a 60 m wide and 1.5 m deep canal was implemented (all dimensions in prototype scale).

As illustrated in Figure 10, the results of the 1:1 numerical model exhibit good agreement with those of the 1:10 numerical model. The comparison of the horizontal force exerted on the column as well as the

bore depth 2 m in front of the column for the tests with and without canal demonstrated good agreement between the 1:1 and scaled 1:10 numerical results. It should be noted that the scale effect on force in the presence of canal is more pronounced, although it is still reasonable. For the scaled model, the bore depth, time, and force were scaled by $1/\lambda$, $1/\lambda^{0.5}$ and $1/\lambda^3$ respectively, where λ is the scale ratio and is equals to 0.1.

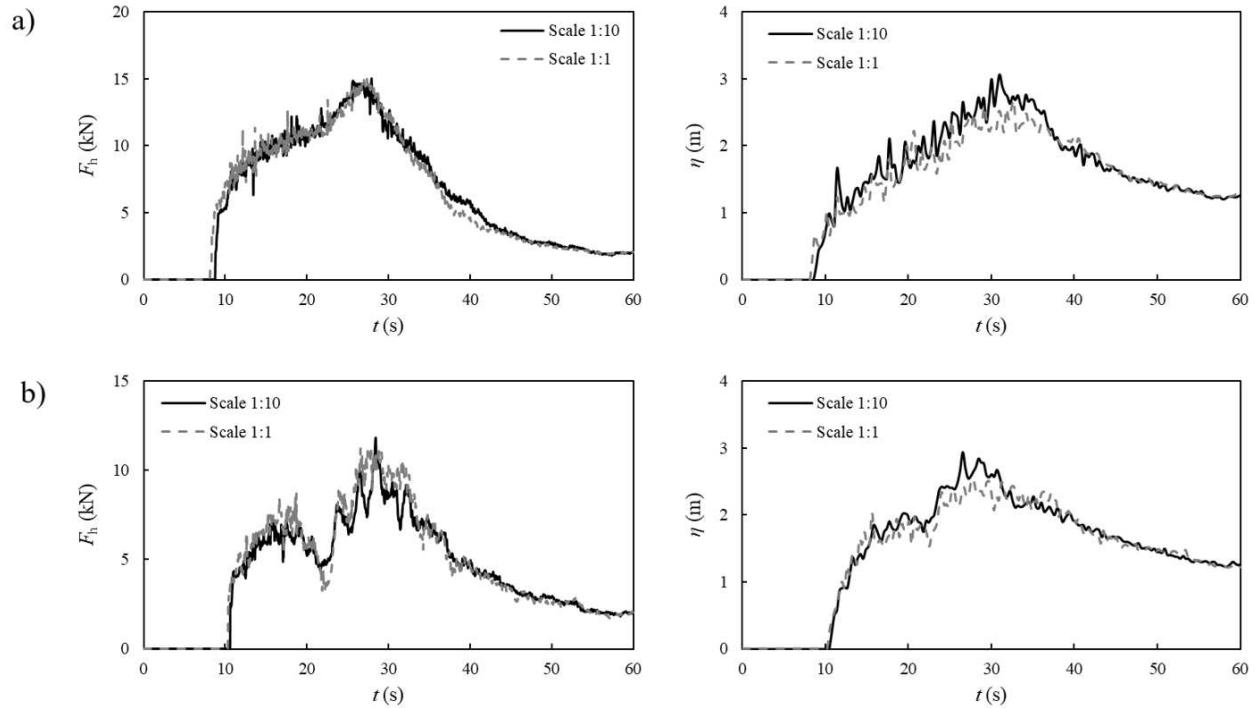


Figure 10: Comparison of the horizontal force on column (left panel) and the bore depth at 2 m front of the column (right panel) for scales of 1:1 and 1:10 for tests. Results are shown for tests without a canal (top row), and with a canal (bottom row)

4.2. Length of flume

For a dam-break problem, the reservoir length is crucial for ensuring a stable bore front during water propagation. A longer reservoir maintains a steady flow, which is essential for stable bore formation (Shugan et al., 2020), where an insufficient reservoir length can cause rapid emptying, leading to unstable bore characteristics (Liu et al., 2020). In addition, the pressure exerted on surfaces varies significantly with bore shape and stability, which is contingent on reservoir length (Issakhov et al., 2020).

In this section three different models with reservoir lengths of 100, 200, and 500 m were chosen, and the time histories of the horizontal forces on the columns were compared. As shown in Figure 11, by increasing the length of the reservoir, the maximum horizontal force on the column remained constant. While a reservoir length of 100 m was sufficient to capture the peak horizontal force exerted on the column, a 500 m long reservoir was ultimately selected to ensure an accurate analysis of the hydrodynamic processes and ensured that the reservoir would not be fully depleted during the 100-second simulation.

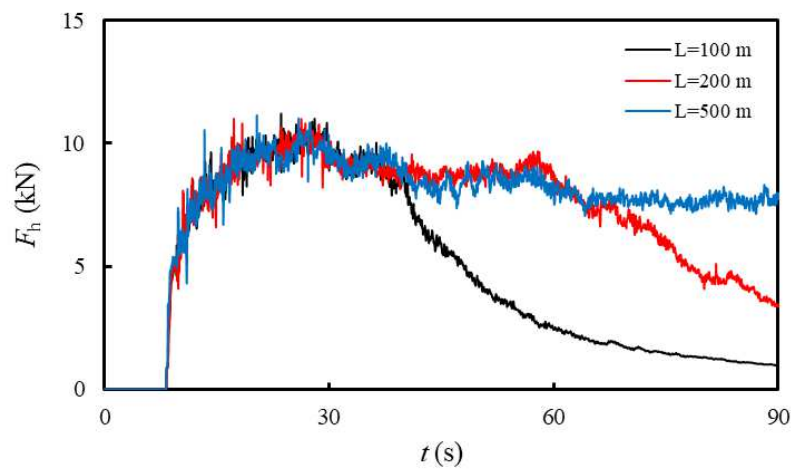


Figure 11: The effect of the reservoir length on horizontal force exerted on the column

4.3. Width of flume

Another limitation of the experimental modeling was related to the flume width. In this regard, wider flumes with widths of 6 m and 10 m were selected, and the flow around the column and the horizontal force on the column were compared with the results of the model with a flume width equal to 3.8 m.

The time history of the horizontal force was plotted for different flume widths to analyze the effects of the flume width on the force exerted on the column. As shown in Figure 12, the maximum horizontal force differs by less than 1% between widths of 3.8 m and 6 m, and the time history of the force shows negligible variations. Increasing the width to 10 m does not significantly affect the results. Therefore, a width of 3.8 m was selected for the numerical modeling tests.

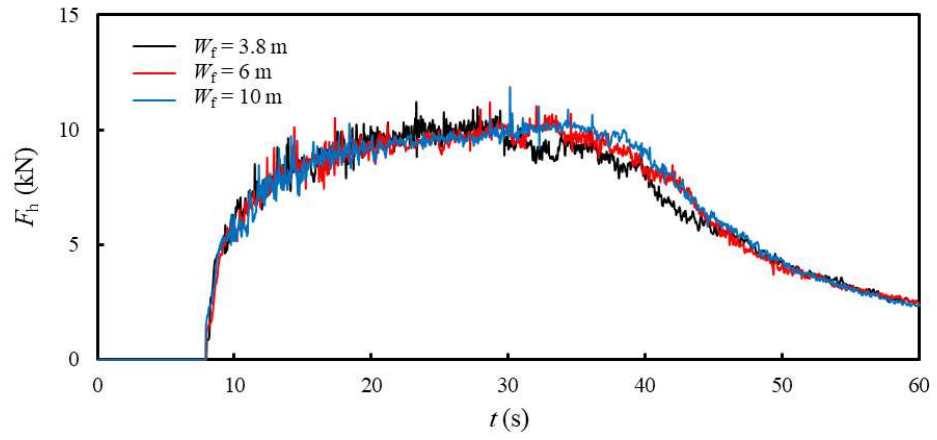


Figure 12: The effect of the reservoir width on horizontal force on the column (test without canal)

5. Results

The primary objective of this study is to investigate the effects of a rectangular water-filled canal on the horizontal force induced by a tsunami bore on a column located behind a canal. By overcoming the constraints of laboratory-scale experimental modeling, numerical simulations were conducted at a prototype scale (1:1) using a flume with a width of 3.8 m, and reservoir length of 500 m. A square column of 40 cm on each side was fixed at $x=72$ m for all the tests. Different dimensions of the canal were considered, and the downstream edge of the canal was positioned at $x=60$ m. The bore was generated by releasing a water impoundment at a depth of 4 m, resulting in a tsunami-like bore with a maximum flow depth of 2.5 m, flow velocities ranging from 4 to 8 m/s. These conditions are representative of the moderate tsunami events that may occur in coastal areas. Consequently, the flow velocities in the model were higher than those typically observed in real-world tsunamis with the same flow depth.

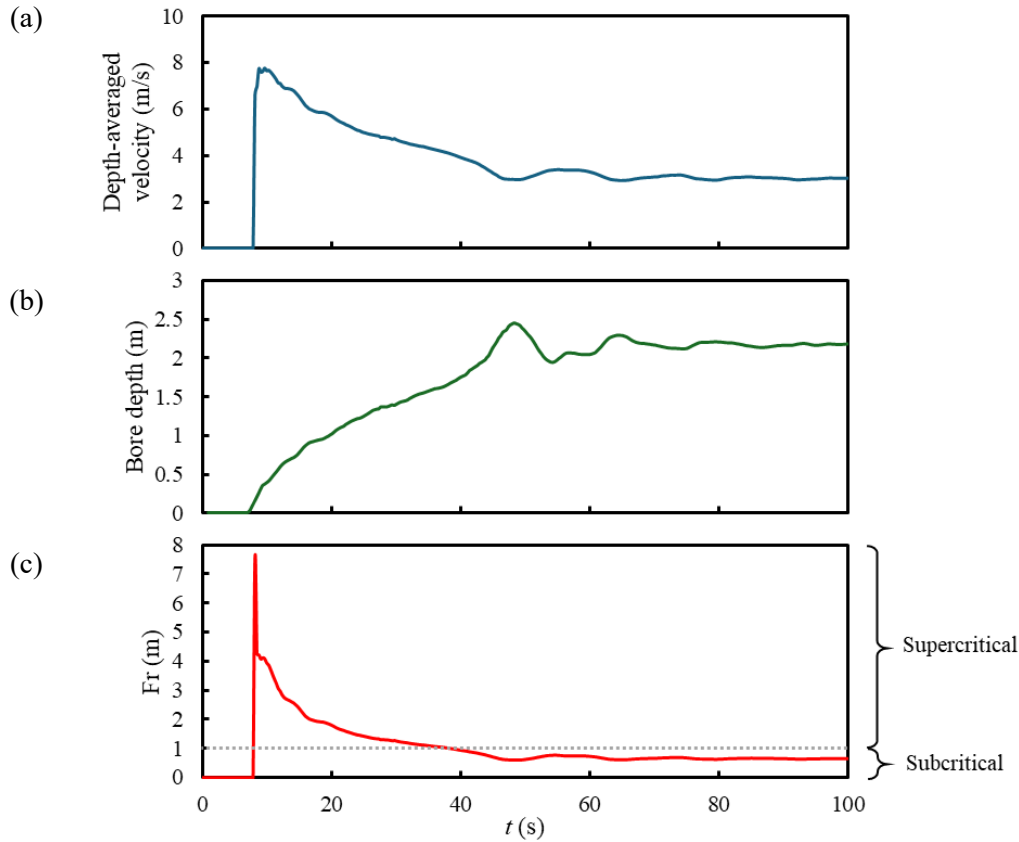
By keeping all parameters constant for all tests, except for the canal dimensions, the test designations were selected based on the width and height of the mitigation canal. For instance, test w30-d1.5 refers to a scenario in which a mitigation canal with a width (w_c) of 30 m and depth (d_c) of 1.5 m.

5.1. Bore interaction with column

The interaction between tsunami bores and a structural column involves complex hydrodynamic regions around the column, and subsequently, forces and pressure distributions on it. Various studies have utilized numerical simulations and experimental setups to analyze these interactions (St-Germain et al. 2014, Palermo et al., 2009). Tsunami bores are characterized by high velocity and turbulent flow, which can exert substantial forces on structures. The bore depth and velocity are crucial factors that influence the pressure exerted on columns (Asadollahi et al., 2019a, b; Chuang et al., 2020).

As illustrated in Figure 13, the time history of the bore depth and depth-averaged velocity for the test without a canal and at $x=70$ m reveals that the bore front initially propagates with a significantly high velocity, which gradually decreases over time. Conversely, the bore depth exhibits an increasing trend as the bore propagates. A combination of high velocity and low bore depth results to a high Froude number

327 $(Fr=\bar{U}/\sqrt{gh_b})$, which creates a supercritical region with a Fr of approximately 8. It should be noted that
 328 calculating the Fr at the moment of wave arrival is challenging and highly susceptible to numerical errors.
 329 By increasing the bore depth and decreasing the bore velocity during this time, Fr drops to lower than 1
 330 around $t(g/d_0)^{0.5}=60$, which means that the flow regime changes from supercritical to subcritical.



331 Figure 13. Time history of (a) bore depth, (b) depth-averaged velocity, and (c) Fr at $x=70$ m for the test without canal and column

332 The interaction between a tsunami-like bore and a column creates a highly turbulent and complex flow
 333 region, which has been the subject of extensive research (Harish et al., 2025; Nouri et al., 2010; Al-Faesly
 334 et al., 2012). The presence of the column significantly influences the surrounding flow pattern. Figure 14
 335 presents the x -velocity distribution along the centerline of the flume ($y=0$) at $t=26$ s, corresponding to the
 336 moment when the horizontal force on the column reaches its peak. As shown in this figure, the presence of
 337 the column reduces the x -direction velocity in the region immediately in front of the structure. By analyzing
 338 the x -direction velocity along the depth at various locations upstream of the column, it is evident that the

column's influence extends approximately 2 m upstream (Figure 15). Because of the obstruction caused by the column, part of the flow is diverted laterally in the y -direction, while another portion moves upward, leading to a run-up on the front face of the column, where the x -velocity remains relatively low.

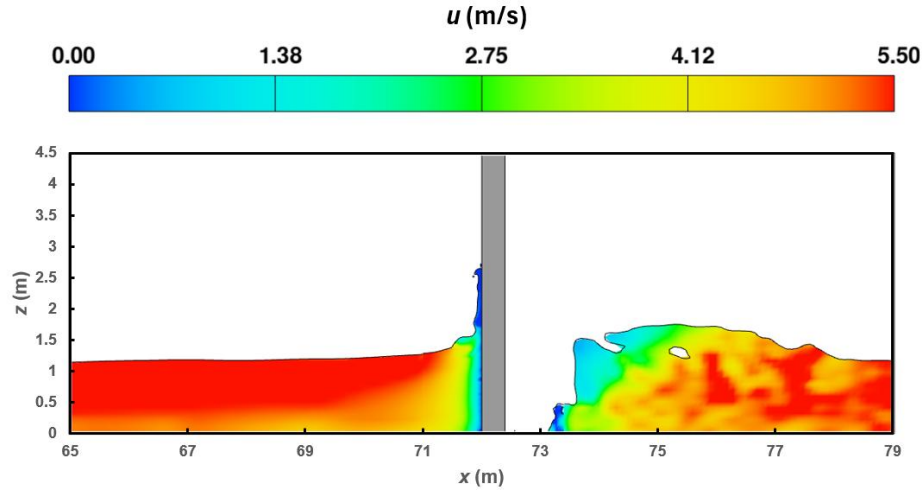


Figure 14. Snapshot of x -velocity pattern around the column at $t=26$ s and $y=0$ (centerline) for the test without canal (NC)

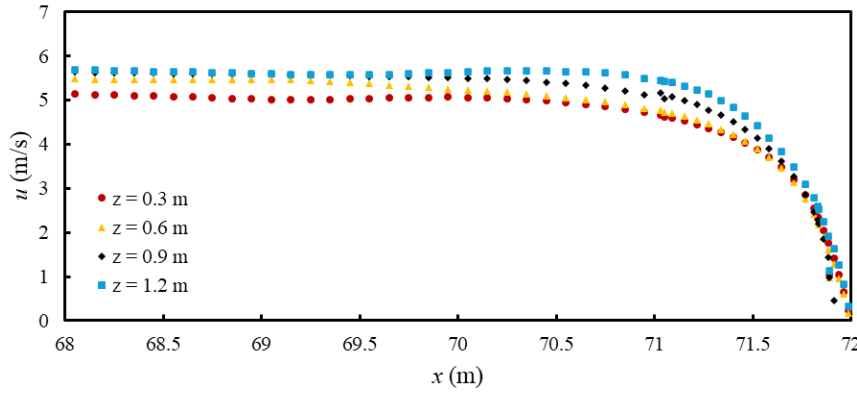


Figure 15. x -direction velocity at different z -levels, $t=26$ s and $y=0$ for the test without canal (NC)

5.2. Bore interaction with canal

The crossing of a tsunami-like bore over a water-filled canal generates large free-surface fluctuations and velocity variations, which can be described as hydraulic jumps (Henderson, 1966; Elsheikh et al, 2022a, b). By reaching the bore to the water-filled canal, it penetrates the canal, which creates a high-turbulence regime, and the interaction of the front bore with the canal causes a reduction in the high velocity of the bore front. Figure 16 shows snapshots of the tsunami-like bore interactions with a rectangular water-filled

canal for test w30-d1.5. As shown in this figure, by entering the bore into the canal, a large volume of water goes out, which makes the bore propagate, but at a smaller velocity.

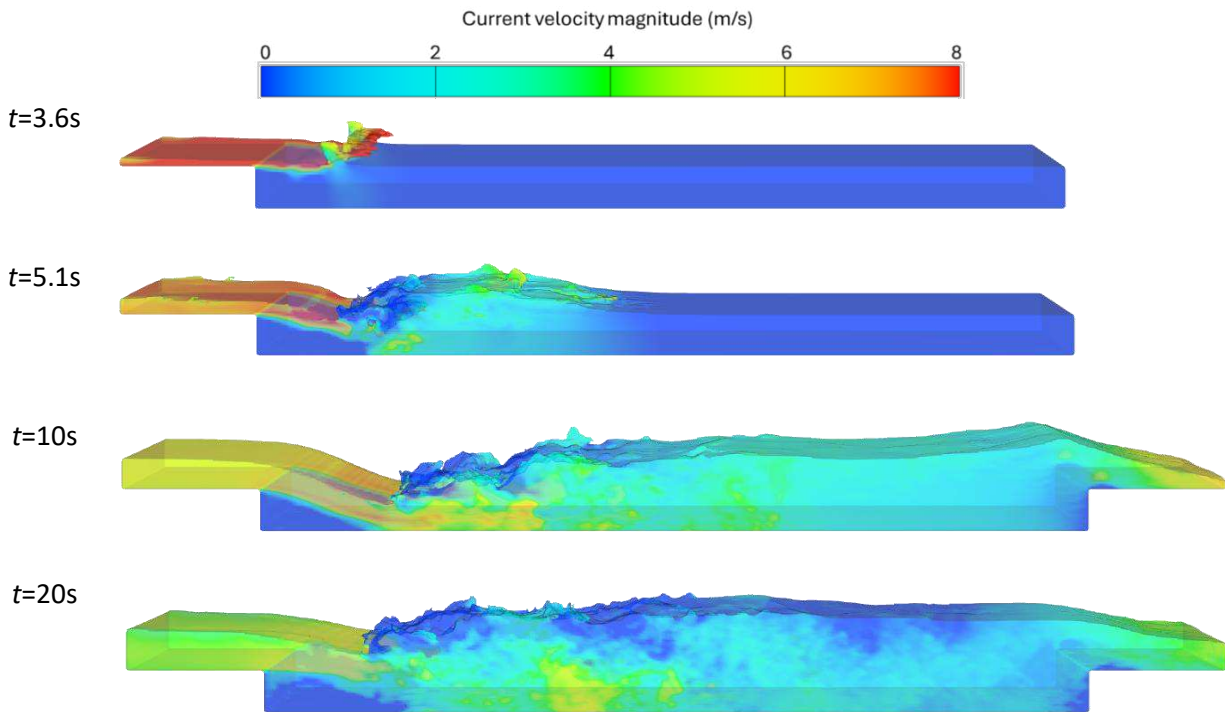


Figure 16: Snapshots of bore interaction with rectangular water filled canal (Test: w30-d1.5)

Figure 17 shows the time history of the x -direction velocity at $z=0$, taken after the canal ($x=65$ m) in test w30-d1.5. These results were compared to those of a test without the presence of a canal (Test NC). The findings reveal that the inclusion of a canal with a width of 30 m and a depth of 1.5 m resulted in a reduction in bore front velocity by approximately 13%. While the presence of the canal increased the arrival time of the bore front, it is important to note that this delay is not significant enough to meaningfully enhance evacuation times during a tsunami event.

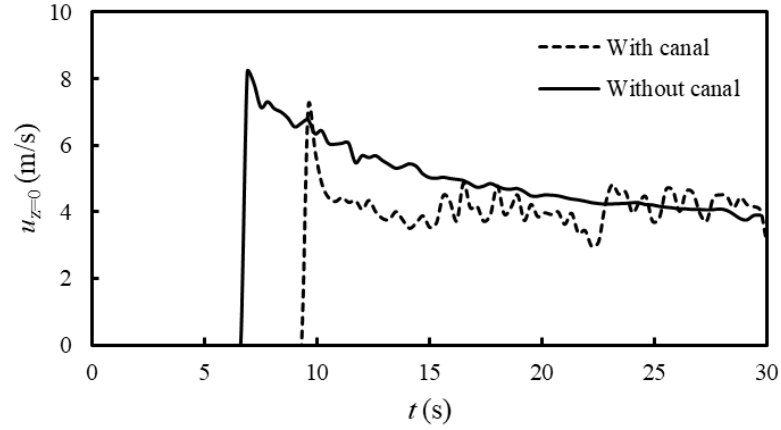


Figure 17: Effect of canal on reducing the bore front velocity at $z=0$ (Test: w30-d1.5 for the test with canal)

While the presence of the canal increased the arrival time of the bore front, it is important to note that this delay is not significant enough to meaningfully enhance evacuation times during a tsunami event.

5.3. Effect of the canal on flow patterns around the column and forces exerted on the column

The interactions between tsunami-like bores and structures have been widely investigated using both experimental (Nistor et al., 2009; Nouri et al., 2010; Al-Faesly et al., 2012) and numerical approaches (Wei et al., 2015; Sarjamee et al., 2017), providing crucial insights into the forces exerted during such events. However, limited research has been conducted on the interaction of tsunami-like bores with water-filled canals (El-sheikh et al., 2022a, b; El-sheikh et al., 2020; Rahman et al., 2017).

Figure 18 presents the time history of x -velocity at 0.5 m above the bed for different combinations of canal and column presence at $x = 70$ m (2 m in front of the column). The presence of canal caused to velocity reduction, accompanied by some oscillations, and significantly reduces the bore front velocity, which is a crucial factor in certain cases, where it contributes to the maximum force exerted on the structures. The presence of the column reduces the flow velocity in the x -direction due to wave reflection, as evidenced by the comparison of the time history of velocity, which the velocity profiles for the case with the column (red and green lines) consistently lie below those for the case without the column (black and blue lines).

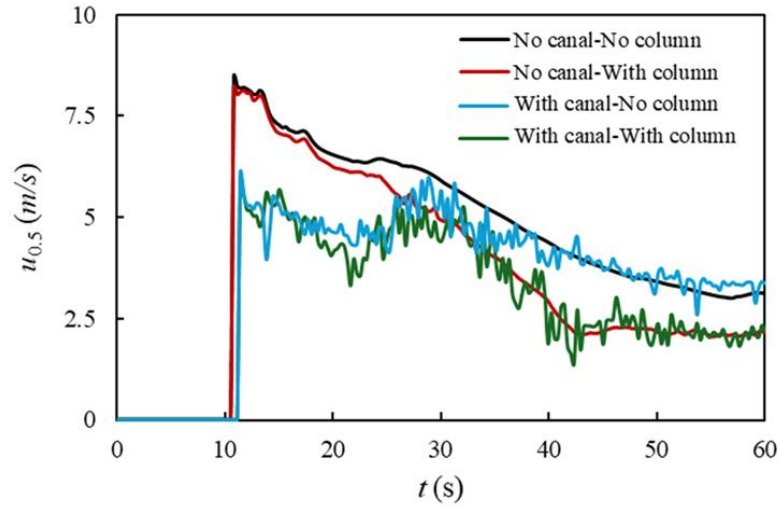


Figure 18: Effect of canal and column existence on x -velocity at $z=0.5$ m, $y=0$, and $x=70$ m (2 m front of the canal)

Figure 19 illustrates the snapshots of the bore front impacting the column, with and without the presence of a 30 m wide and 1.5 m deep canal. For a better comparison, the bore-front arrival time to the column was selected as the origin of the time in this figure. The presence of the canal reduces the bore-front velocity and results in smaller splashes and run-up both in front of and downstream of the column, while simultaneously causing the bore to reach the column with a higher water depth.

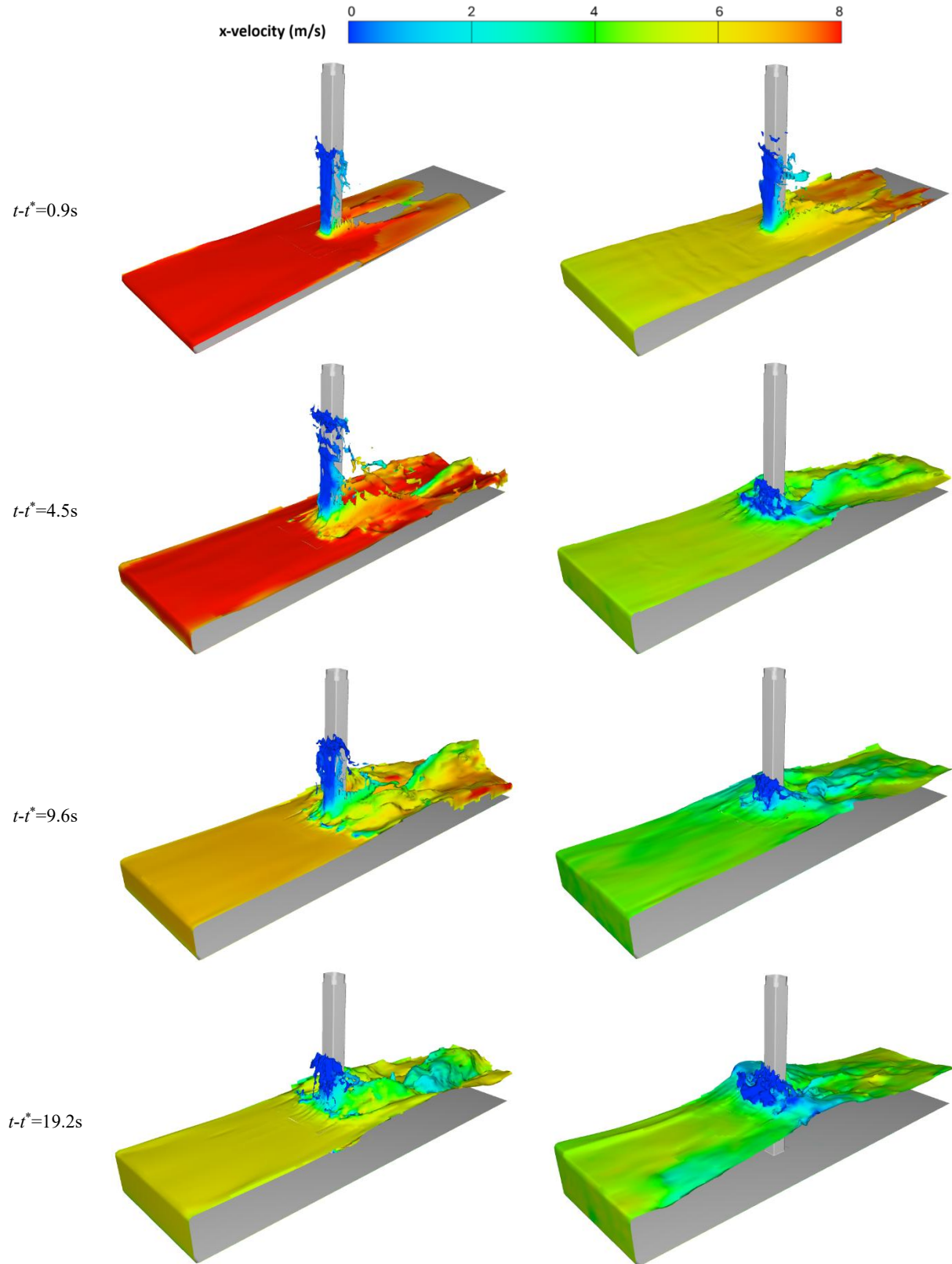


Figure 19: Snapshots of the bore front impact on the column without presence of the canal (left panel) and with presence of canal (right panel) at different time steps (t^* is bore arrival time to the column)

To quantitatively compare the effect of the canal, Figure 20 shows the time histories of the bore height, depth-averaged velocity, momentum flux at $x=70$ m (2 m in front of the column), and horizontal force exerted on the column. These graphs illustrate that the canal increases the bore front depth while decreasing the depth-averaged velocity in front of the column, which are two main factors determining the momentum flux, and therefore the force on the column, which means the canal influences them in opposite ways. In particular, the canal's reduction of the x -velocity (which is squared in the momentum flux calculation) outweighs its effect on increasing the bore front depth, ultimately resulting in a decrease in the overall momentum flux. For better comparison, the graphs plotted based on arrival time using $t-t^*$ on the horizontal axis.

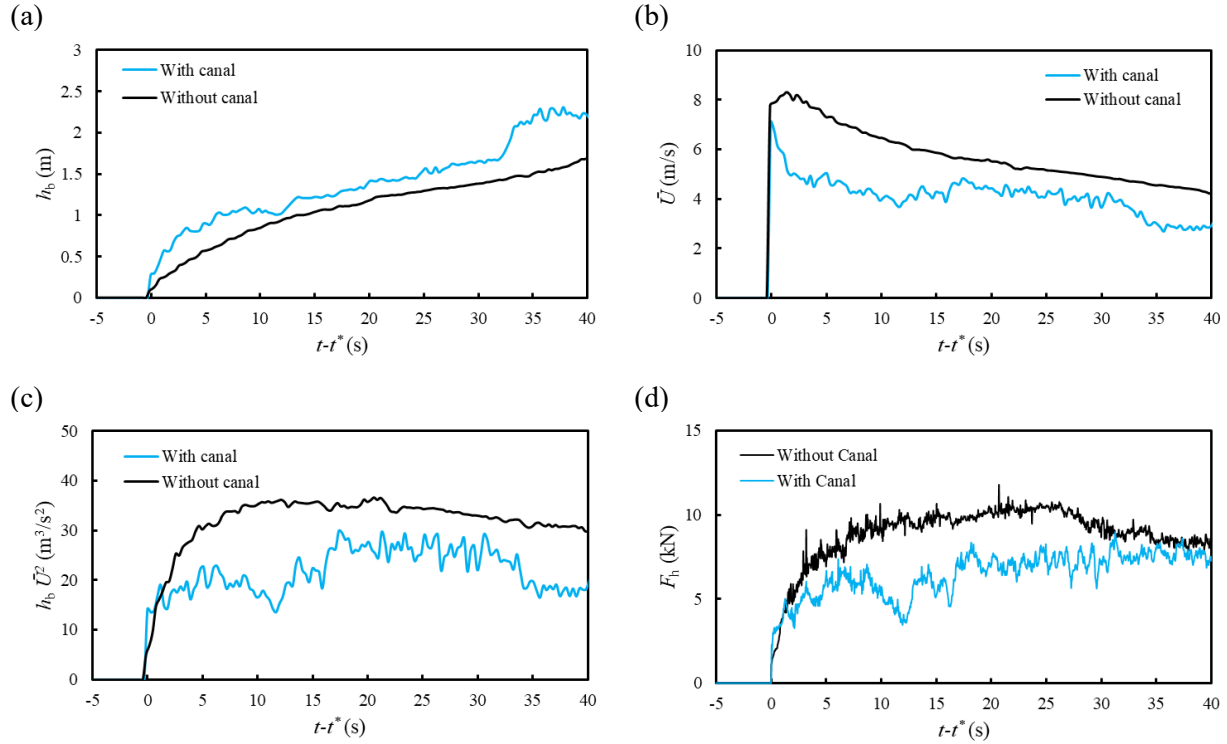


Figure 20: Time history of (a) the bore depth (h_b), (b) the depth-averaged velocity ($\bar{U}$), (c) the momentum flux density per unit width ($h_b \bar{U}^2$), and (d) the horizontal force exerted on the column at $x=70$ m, with (blue line) and without (black line) presence of a 30 m wide and 1.5 m deep canal

The pressure distribution in front of the column with and without the presence of a canal is shown in Figure 21. The canal causes some oscillations in the water surface level, leading to a more fluctuating pressure distribution, as shown in Figure 21b (with the canal present), compared to the smoother distribution

without the presence of the canal (Figure 21a). However, the most important note from the comparison in Figure 21 is the lower pressure observed during the initial impact of the bore on the column (between $t=10$ s and 20 s) in the presence of the canal. The presence of the canal reduces the maximum pressure exerted on the column during the first 15 seconds of bore impact, with a reduction ranging from 20% to 50%. Studies by Arikawa (2009) and Ramsden and Raichlen (1990) revealed that under specific bore and structure conditions, the force exerted on structures during the initial impact of a tsunami bore can exceed the quasi-steady force due to the sudden and intense collision of the bore front with the structure. This reveals that the reduction in bore pressure, and consequently the force on the column during the initial impact of a tsunami-like bore, due to the presence of canals, has a significant effect on protecting coastal infrastructure.

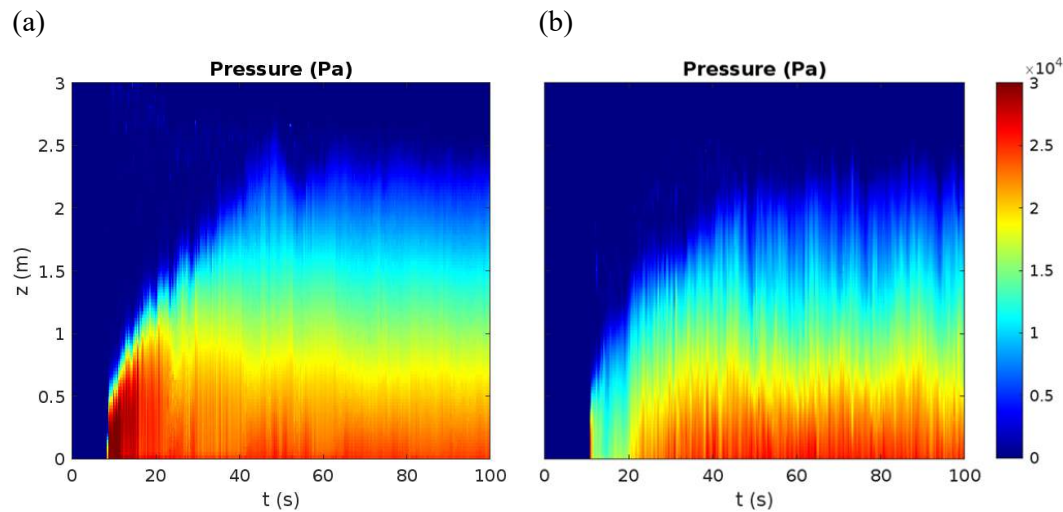


Figure 21: Pressure distribution on the column, (a) without canal (test NC), and (b) with canal (test w30-d3)

Figure 22 illustrates the flow pattern around the column and the influence of the canal presence on these patterns. The figure compares the flow around the column with and without a canal with a width of 30 m and depth of 3 m at $t=26$ s (when the force is at its maximum) and $z=0$. As shown in this figure, the shorter vectors in the test with the canal indicate that the canal creates a calmer region, particularly behind the column and along its edges. This reduction in flow velocity is a critical factor in mitigating scouring around the column, which is one of the main contributors to structural failure. The absence of black vectors behind

the column indicates the formation of a wake, which creates an empty region. However, in the presence of the canal, this area is not empty, as the canal helps to calm the flow and reduce the wake effect.

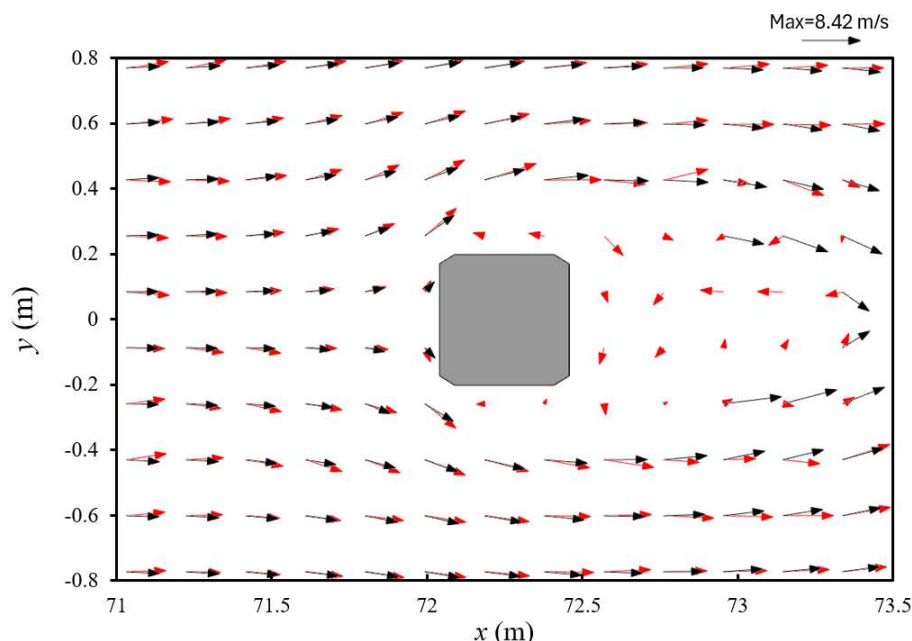


Figure 22: Velocity vectors around the column at $t=26$ s and $z=0$ without (black) and with (red) presence of a 30 m wide and 3 m deep canal

5.4. The effects of canal dimensions

To study the effects of canal dimensions on the attenuation rate of the horizontal force exerted on the column, a series of numerical modeling with different widths and depths of canals was performed. As mentioned previously, the test designations were determined based on the canal width (d_c) and canal depth (w_c). All tests were performed with the same water impoundment depth of 4 m and the upstream edge of the canal and column located at $x=20$ m and at $x=72$ m, respectively.

Table 2 lists the configuration parameters in the numerical simulations. In the first test, no canal was considered (NC), and in the next tests, canals with depths of 0.5, 1.5, 3, and 4.5 m and widths of 10, 20, 30, and 40 m were considered.

438

Table 2. Numerical modeling tests

Test No.	Test name	w_c (m)	d_c (m)
1	No Canal (NC)	-	-
2	w10-d3	10	3
3	w20-d3	20	3
4	w30-d3	30	3
5	w40-d0.5	40	0.5
6	w40-d1.5	40	1.5
7	w40-d3	40	3
8	w40-d4.5	40	4.5

439

440 Figure 23 and Figure 24 illustrate the time history of the horizontal force exerted on the column for
441 different canal dimensions. For better understanding, the bore arrival time was considered for the horizontal
442 axis. By comparing the time histories, it is clear that the presence of the canal reduces the force exerted on
443 the column, which increases the rate of attenuation by increasing the depth or width of the canal. Although,
444 as shown in these figures, the canal's presence effects are significant in the initial impact and run-up regions
445 ($t-t_0 < 40$ s), the presence of the canal causes fluctuations in the horizontal force, which makes it more
446 difficult to study the effects of the canal dimensions on the reduction factor by comparing the maximum
447 amount of the force exerted on the column, especially in the quasi-steady region ($t-t_0 > 50$ s). In this regard,
448 the average of the force during the first 25 s was selected, and the effects of the dimensions of the canal
449 were studied and compared, as depicted in Figure 25.

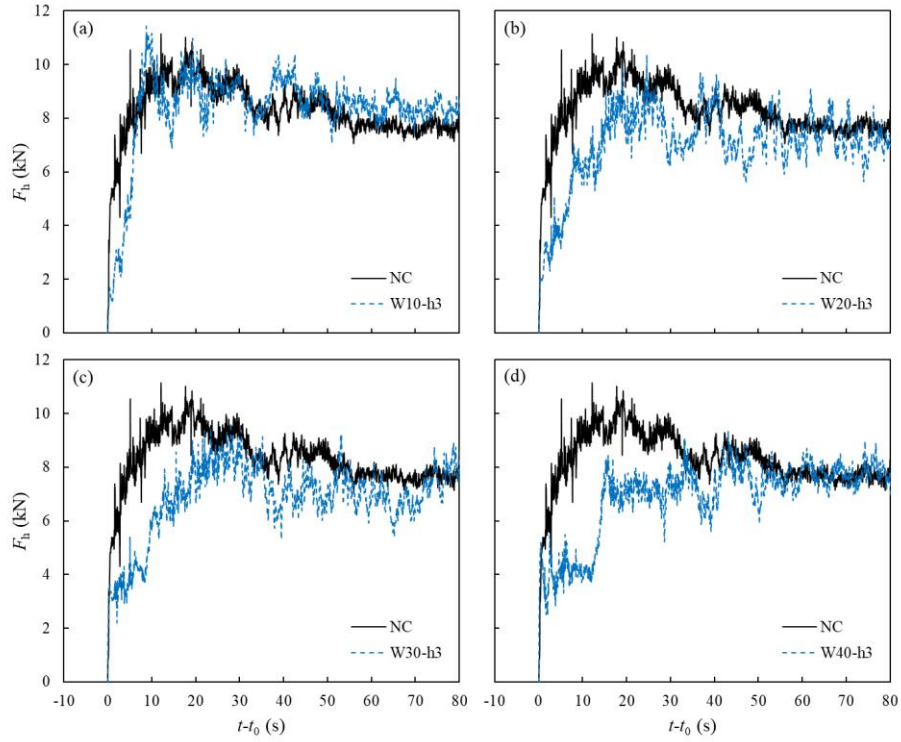


Figure 23: Comparison of the time history of the horizontal force exerted on the column for a canal with a depth of 3 m and various width of (a) 10, (b) 20, (c) 30, and (d) 40 m with a test without canal (NC)

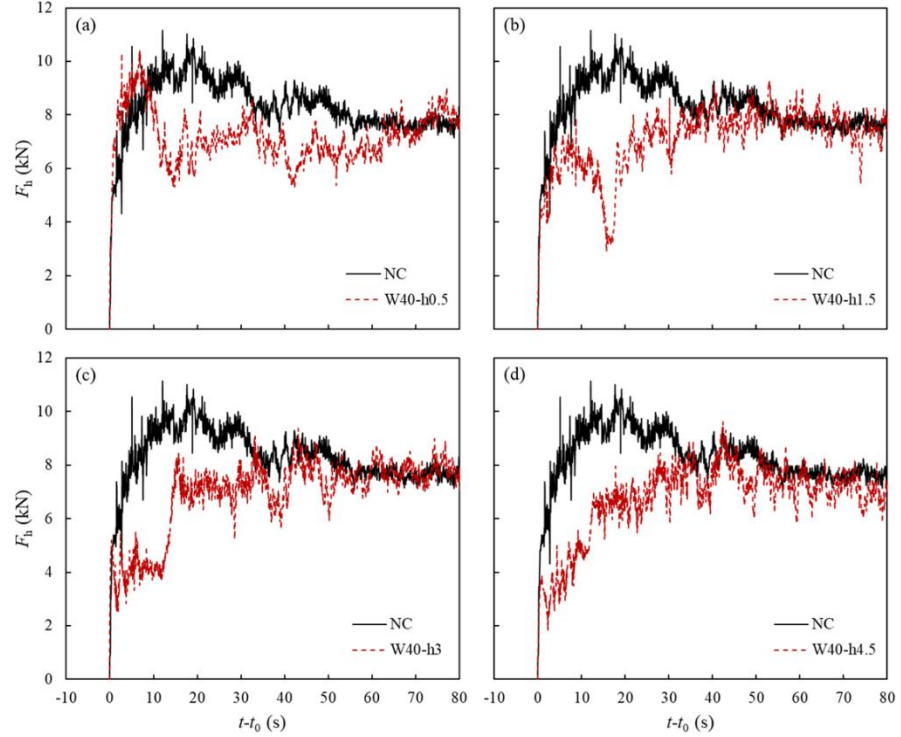


Figure 24: Comparison of the time history of the horizontal force exerted on the column for a canal with a width of 40 m and various depth of (a) 0.5, (b) 1.5, (c) 3, and (d) 4.5 m with a test without canal (NC)

As shown in Figure 25(a), increasing the canal depth beyond a certain threshold did not lead to a significant improvement in the force reduction factor. For example, in the case of a tsunami-like bore generated by a 4 m dam break, when the canal width is fixed at 40 m, the threshold depth is approximately 3 m. This indicates that further increasing the canal depth to 4.5 m results in a negligible additional reduction in the force exerted on the column.

Conversely, Figure 25(b) clearly illustrates that increasing the canal width substantially enhanced the reduction in horizontal forces on the column. For a canal with a constant depth of 3 m, increasing the width from 10 to 40 m significantly increased the reduction rate from approximately 11% to 37%. This indicates that canal width plays a more dominant role than depth in mitigating tsunami-like bore forces, emphasizing the importance of lateral expansion in canal design for improved energy dissipation, as reported by Rahman et al. (2017) and Elsheikh et al. (2022a, b).

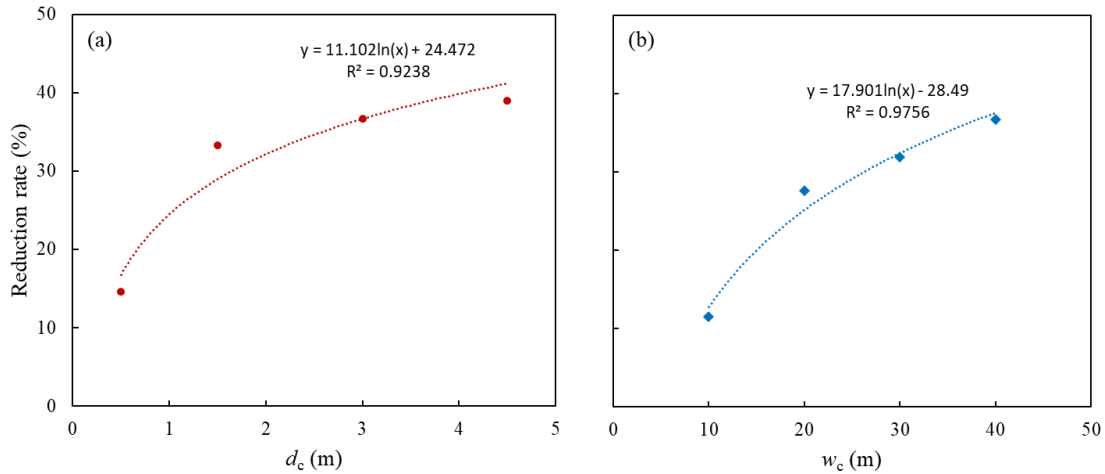


Figure 25: Effects of canal's dimensions on the reduction rate of horizontal force exerted on column due to the presence of canal with (a) different depth of canal with a width of 40 m, and (b) different width of canal for a canal with a depth of 3 m

6. Discussion

Tsunamis are rare events that are difficult to study through field experiments. Therefore, most studies on tsunami propagation and its interactions with structures on affected coastlines rely on laboratory experiments and numerical simulations. To reduce these impacts, both nature-based and engineered

solutions have been implemented. Among these, water-filled canals aligned parallel to coastlines have shown the potential for dissipating tsunami energy and reducing the intensity of coastal inundation.

This study investigated the role of a rectangular water-filled canal in reducing the force exerted by a tsunami-like bore on a vertical column located in front of the canal. A series of calibrated numerical simulations using FLOW-3D were performed to evaluate how the canal affects bore dynamics and its interaction with both the canal and column. To overcome the limitations of small-scale experiments, full-scale numerical models have been developed using realistic tsunami parameters and practical canal and column dimensions. The results showed that scaling effects had negligible influence on the results of the time history of the bore depth and force exerted on the column. However, full-scale modeling better captured the high-turbulence zone generated by the interaction of the bore with the canal and the column.

In the laboratory experiments, due to the limited flume length, a reservoir with a wider width than the flume was constructed behind the gate to hold enough water volume. However, the non-rectangular geometry of the reservoir influenced the bore characteristics and resulting forces. To simulate different canal depths in the experimental tests, some boxes were placed on the flume bed, while a 1:6 sloped bed was added upstream of the gate to suppress vortex formation. These features were removed from the numerical models, which assumed the same level of bed throughout the domain, producing results that are more representative of real tsunami behavior. The extended reservoir length (up to 500 m) in the simulations prevented depletion over the 100 s runtime, ensuring continuous and realistic bore evolution. The flume width was kept the same as in the experiments because changes showed no significant effect.

The turbulence generated as the bore passed through the water-filled canal played a key role in dissipating the energy and reducing the force exerted on the column. Notably, the canal significantly changed the flow regime and reduced the bore velocity, especially the bore front velocity. Time-history comparisons confirmed that the canal had a stronger influence on reducing the initial impact force than on reducing the later quasi-steady force.

The findings of this study are consistent with those of Rahman et al. (2017), who also investigated canals as tsunami mitigation measures. Their results indicated that while canals could partially absorb tsunami energy, they also caused reflected waves that led to variations in inundation depth compared with cases without canals. Their experiments showed that deeper and wider canals resulted in greater reductions in the wave impact. Similarly, Elsheikh et al. (2022) found that wider canals were more effective at reducing the momentum of tsunami bores, while deeper canals absorbed more energy as the bore passed through. Their experimental and numerical results also indicated that canals led to an increased maximum bore depth landward of the canal while reducing the bore's velocity. These findings align closely with those of the present study, in which increased canal width and depth led to energy dissipation, velocity reduction, and force mitigation. However, it appeared that canal depth had a threshold for a certain tsunami event which beyond a certain point, increasing depth and width did not lead to further reductions in force. In the present study, for a canal width of 40 m, the threshold depth is approximately 3 m, beyond which further increases in canal depth do not significantly change the reduction factor.

Despite these promising results, several limitations of this study remain to be acknowledged. Sediment transport, debris flow, and scour effects were not modeled, although they are crucial in real tsunami scenarios. The studied structure was limited to a single square column.

Future research should explore:

- The incorporation of finer grid, more advanced turbulence models, and wider range of simulation parameters,
- Larger full-scale domains and more canals configurations,
- The influence of canal location and its distance from the structure,
- The performance of canals in multi-column arrangements,
- The inclusion of debris impact, sediment transport, and scour,
- Cost-benefit analysis and feasibility of implementing water-filled canals in real-world coastal cities.

Overall, the findings of this study contribute to the understanding of using engineered water-filled canals as a tsunami mitigation measure and emphasize the need for further investigation to develop practical design guidelines for protecting coastal infrastructure.

7. Conclusion

This study investigated the effectiveness of a rectangular water-filled canal as a potential mitigation measure to reduce the energy of a tsunami-like bore impacting a column using a series of numerical modeling simulations. FLOW-3D was employed as a robust tool capable of simulating complex fluid-structure interactions. To calibrate the numerical model, experimental tests were conducted in the Water Resources Engineering Laboratory at the University of Ottawa, Canada, using a flume measuring 15.60 m in length, 0.38 m in width, and 0.60 m in depth. In the experimental tests, various canal configurations were tested with depths of 5, 10, and 15 cm and widths of 60, 160, and 300 cm. The results from the numerical simulations were compared with the experimental data in terms of the bore depth before and after the canal, as well as the force exerted on the column. The numerical domain was designed to replicate the experimental flume. Among the turbulence models available in FLOW-3D, the Smagorinsky model was chosen due to its ability to capture the complex interaction between the tsunami-like bore, the water-filled canal, and the column.

To overcome certain limitations of the physical experiments, numerical simulations were conducted at the prototype scale, and the reservoir length was extended to 500 m to ensure a sufficient volume of water behind the gate, allowing the simulations to run for 100 seconds without depletion, thereby maintaining consistent bore characteristics. The flume width was set to 3.8 m, matching the laboratory flume size, and the study showed that increasing the width had no significant effect on the results. The calibrated model at real-world scale was then used to analyze the performance of the water-filled canal as a tsunami mitigation strategy. The propagation of the tsunami-like bore and its interaction with the canal and the column were thoroughly examined. The column size was set to 40 cm, which is comparable to that of a typical residential

building column in the real world. Comparisons of the time histories of the bore depth and impact force on the column demonstrated a good agreement between the numerical and experimental results.

In the present study, various canal widths and lengths were analyzed. Although increasing both the width and depth of the canal enhanced energy dissipation and consequently reduced the force on the column, the results suggest that there is a limit to the reduction factor. Beyond this limit, which depends on the characteristics of the tsunami bore, further increases in canal dimensions do not lead to significant additional force reduction. For a tsunami-like bore generated by the sudden release of a 4 m water impoundment behind a gate, the horizontal force reduction factor was approximately 40% for a canal with a width of 40 m and a depth of 4.5 m. Notably, increasing the canal width had a more significant effect on force reduction than increasing the depth. However, there is a threshold for both depth and width of the canal which further depth and width increases had a minimal impact.

Overall, this study confirms that water-filled canals can reduce tsunami-induced forces on structures located near coastlines by approximately 40%. These findings suggest that such canals are viable passive mitigation measures. Further studies are recommended to develop practical design guidelines for determining the optimal dimensions of protective water-filled canals for infrastructure in tsunami-prone coastal zones.

566 **Declarations**

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569 **Conflict of Interest:** The authors declare no conflicts of interest.

570 **Ethics Approval:** Not applicable.

571 **Consent to Participate / Publish:** Not applicable.

572 **Availability of Data and Materials:** All data generated or analyzed during this study are available from
573 the corresponding author upon reasonable request.

574 **Authors' Contributions:** Reza performed the numerical modeling and the analysis and drafted the
575 manuscript. Prof. Mohammadian and Prof. Nistor supervised the research and provided substantial
576 revisions. All authors read and approved the final manuscript.

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References

- Al-Faesly, T., Palermo, D., Nistor, I., & Cornett, A. (2012). "Experimental modeling of extreme hydrodynamic forces on structural models." *International Journal of Protective Structures*, 3(4), pp. 477-505.
- Alemi, M., & Maia, R. (2018). "Numerical Simulation of the Flow and Local Scour Process around Single and Complex Bridge Piers." *International Journal of Civil Engineering*, 16, 475-487. <https://doi.org/10.1007/s40999-016-0137-8>
- Alongi, M. D. (2008). Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change, *Estuarine, Coastal and Shelf Science* Volume 76, Issue 1, Pages 1-13. <https://doi.org/10.1016/j.ecss.2007.08.024>
- April-Le Quéré, P., Nistor, I., Mohammadian, A., Schimmels, S., Schendel, A., Goseberg, N., Welzel, M., Krautwald, C., & Stolle, J. (2022). Hydrodynamics and associated scour around a free-standing structure due to turbulent bores. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 148(5). [https://doi.org/10.1061/\(ASCE\)WW.1943-5460.0000717](https://doi.org/10.1061/(ASCE)WW.1943-5460.0000717)
- Arefi, R., Nistor, I., Mohammadian, A., & Elsheikh, N. (2025). Effects of a rectangular water-filled canal on bore induced horizontal force exerted on a nearshore structure. *Natural Hazards*, 121, 23197-23237. <https://doi.org/10.1007/s11069-025-07709-y>
- Arikawa, T. (2009). "Structural behavior under impulsive tsunami loading." *Journal of Disaster Research*, 4(6), 377-381.
- Asadollahi, N., Nistor, I., & Mohammadian, A. (2019a). "Numerical investigation of tsunami bore effects on structures, part I: drag coefficients." *Natural Hazards*, 96, 285-309. <https://doi.org/10.1007/s11069-018-3542-2> Springer
- 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." *Natural Hazards*, 96, 331-351. <https://doi.org/10.1007/s11069-018-3544-0>
- Bryant, E., 2014. *Tsunami: the underrated hazard*. third ed. Springer, Chichester, UK.
- Chock, Gary., Robertson, I. N., Kriebel, D. L., Francis, Mathew., & Nistor, Ioan. (2013). *Tohoku, Japan, Earthquake and Tsunami of 2011: performance of structures under tsunami loads*. American Society of Civil Engineers.
- Chuang, W.L., Chang, K.A., Kaihatu, J., Cienfuegos, R., & Mokrani, C. (2020). "Experimental study of force, pressure, and fluid velocity on a simplified coastal building under tsunami bore impact." *Natural Hazards*, 103, 1093-1120. <https://doi.org/10.1007/s11069-020-04027-3>
- Elsheikh, N., Azimi, A. H., Nistor, I., & Mohammadian, A. (2020). Experimental Investigations of Hydraulic Surges Passing over a Rectangular Canal. *Journal of Earthquake and Tsunami*, 14(5). <https://doi.org/10.1142/S1793431120400047>

- Elsheikh, N., Nistor, I., Azimi, A. H., & Mohammadian, A. (2022a). Tsunami-Induced Bore Propagating over a Canal, Part I: Laboratory Experiments and Numerical Validation. *Fluids*, 7(7). <https://doi.org/10.3390/fluids7070213>
- Elsheikh, N., Azimi, A. H., Nistor, I., & Mohammadian, A. (2022b). Tsunami-Induced Bores Propagating over a Canal, Part II: Numerical Experiments Using the Standard k- ϵ Turbulence Model. *Fluids*, 7(7). <https://doi.org/10.3390/fluids7070214>
- Ghasemi, A., Amirabadi, R., & Kamalian, U.R. (2023). "Numerical investigation of hydrodynamic responses and statistical analysis of imposed forces for various geometries of the crown structure of caisson breakwater." *Marine Geology*. <https://doi.org/10.1016/j.margeo.2023.107142>
- Harish, S., Schüttrumpf, H., Sriram, V., & Sannasiraj, S. A. (2025). Tsunami bore impingement on the rectangular structure of different widths: Analysis of maximum impulsive force. *Ocean Engineering*, 319. <https://doi.org/10.1016/j.oceaneng.2024.120191>
- Heidarzadeh, M., Rabinovich, A., Kusumoto, S., & Rajendran, C. P. (2020). Field surveys and numerical modelling of the 2004 December 26 Indian Ocean tsunami in the area of Mumbai, west coast of India. *Geophysical Journal International*, 222(3), 1952–1964. <https://doi.org/10.1093/gji/ggaa277>
- Henderson, F.M. (1966). *Open Channel Flow*. Macmillan, New York.
- Inagaki, N., Nishida, Y., Mikami, T., Nakamura, R., Nistor, I., Soltanpour, M., Goseberg, N., & Shibayama, T. (2025). Field survey of the 2024 Noto Peninsula Earthquake and Tsunami in Japan: Characteristics of damage patterns to coastal communities. *Ocean Engineering*, 316. <https://doi.org/10.1016/j.oceaneng.2024.119765>
- Issakhov, Alibek, Medina, Imanberdiyeva. (2020). Numerical Study of the Movement of Water Surface of Dam Break Flow by VOF Methods for Various Obstacles. *International Journal of Nonlinear Sciences and Numerical Simulation*, 21(5):475-500. doi: 10.1515/IJNSNS-2018-0278
- Lauber, G., & Hager, W. H. (1998). Experiments to dambreak wave: Horizontal channel. *Journal of Hydraulic Research*, 36(3), 291–307. <https://doi.org/10.1080/00221689809498620>
- Liu., Jiaqi, Masoud, Hayatdavoodi., R., Cengiz, Ertekin. (2020). On Bore Dynamics and Pressure: RANS, Green-Naghdi, and Saint-Venant Equations. *Journal of Offshore Mechanics and Arctic Engineering-transactions of The Asme*, 142(2):021902-. doi: 10.1115/1.4044988
- Nistor, I., Nouri, Y., Palermo, D., & Cornett, A. (2009). Experimental Investigation of the Impact of a Tsunami-Induced Bore on Structures. 3324–3336. https://doi.org/10.1142/9789814277426_0275
- Nouri, Y., Nistor, I., Palermo, D., & Cornett, A. (2010). Experimental investigation of tsunami impact on free standing structures. *Coastal Engineering Journal*, 52(1), 43–70. <https://doi.org/10.1142/S0578563410002117>
- Oetjen, J., Sundar, V., Venkatachalam, S., Reicherter, K., Engel, M., Schüttrumpf, H., & Sannasiraj, S. A. (2022). A comprehensive review on structural tsunami countermeasures. In *Natural Hazards* (Vol. 113, Issue 3, pp. 1419–1449). Springer Science and Business Media B.V. <https://doi.org/10.1007/s11069-022-05367-y>

- Palermo, D., I. Nistor, Y. Nouri, and A. Cornett. 2009. Tsunami loading of near-shoreline structures: a primer. *Canadian Journal of Civil Engineering* 36:1804–1815.
- Rahman, M. M., Schaab, C., & Nakaza, E. (2017). Experimental and Numerical Modeling of Tsunami Mitigation by Canals. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 143(1). [https://doi.org/10.1061/\(asce\)ww.1943-5460.0000355](https://doi.org/10.1061/(asce)ww.1943-5460.0000355)
- Ramsden, J.D., & Raichlen, F. (1990). "Forces on Vertical Wall Caused by Incident Bores." *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 116(5), 592–613. [https://doi.org/10.1061/\(ASCE\)0733-950X\(1990\)116:5\(592\)](https://doi.org/10.1061/(ASCE)0733-950X(1990)116:5(592))
- Sarjamee, S., Nistor, I., & Mohammadian, A. (2017). "Numerical investigation of the influence of extreme hydrodynamic forces on the geometry of structures using OpenFOAM." *Natural Hazards*, 87, 213–235.
- Shugan., I. V., Yang-Yih, Chen., Cheng-Jung, Hsu. (2020). Experimental and Theoretical Study on Flood Bore Propagation and Forerunner Generation in Dam-Break Flow. *Physics of Wave Phenomena*, 28(3):274-284. doi: 10.3103/S1541308X20030188
- St-Germain, P., I. Nistor, R. Townsend, and T. Shibayama. 2013. Smoothed-particle hydrodynamics numerical modeling of structures impacted by tsunami bores. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 140:66–81.
- Suppasri, A., Shuto, N., Imamura, F., Koshimura, S., Mas, E., & Yalciner, A. C. (2013). Lessons Learned from the 2011 Great East Japan Tsunami: Performance of Tsunami Countermeasures, Coastal Buildings, and Tsunami Evacuation in Japan. *Pure and Applied Geophysics*, 170(6–8), 993–1018. <https://doi.org/10.1007/s00024-012-0511-7>
- Syamsidik, B., Umar, M., Margaglio, G., & Fitrayansyah, A. (2019). Post-tsunami survey of the 28 September 2018 tsunami near Palu Bay in Central Sulawesi, Indonesia: Impacts and challenges to coastal communities. *International Journal of Disaster Risk Reduction*, 38. <https://doi.org/10.1016/j.ijdr.2019.101229>
- Synolakis, C. E., & Bernard, E. N. (2006). Tsunami science before and beyond Boxing Day 2004. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 364(1845), 2231–2265. <https://doi.org/10.1098/rsta.2006.1809>
- Thanyamanta, W., Herrington, P., & Molyneux, D. (2011). "Wave patterns, wave induced forces and moments for a gravity based structure predicted using CFD." *Proceedings of the ASME 2011, 30th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2011)*, Rotterdam, The Netherlands.
- Wei, Z., Dalrymple, R. A., Hérault, A., Bilotta, G., Rustico, E., & Yeh, H. (2015). SPH modeling of dynamic impact of tsunami bore on bridge piers. *Coastal Engineering*, 104, 26–42. <https://doi.org/10.1016/j.coastaleng.2015.06.008>
- Yang, M., Tang, Y., Wang, L., Zhao, F., & He, S. (2025). Experimental and numerical investigation of flow field characteristics and local scour around trapezoidal artificial reefs. *Ocean Engineering*, 317. <https://doi.org/10.1016/j.oceaneng.2024.120038>