

# Experimental Study on Normalized Bed Shear Stress of Tsunami Bore

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**Abstract.** This study examined the normalized bed shear stress and normalized bore height in tsunami bores over smooth wet-bed surface conditions through laboratory experiments. A spring-loaded vertical lift gate was utilized to generate bores with three initial reservoir depths. Depth-averaged velocity and local water depth measurements were used to calculate bed shear stress based on the Saint-Venant momentum equation. Results show that normalized peak bed shear stress consistently increases with bore intensity, confirming the critical role of bore height in shaping energy transfer and sediment movement. Comparisons with previous datasets validate the consistency and reliability of the experimental design within the tested parameter range.

The results demonstrated that both calculated bed shear stress and depth-averaged velocity increased with initial reservoir depth, confirming that larger bores transfer more energy and generate greater turbulence. However, normalized peak bed shear stress exhibited a nonlinear trend. Further analysis of normalized bore height revealed that larger bores caused amplified surface oscillations and prolonged turbulence, reducing post-peak hydrodynamic stability.

These findings provide baseline data for understanding tsunami bore dynamics, supporting coastal infrastructure design, and sediment transport mitigation strategies to withstand tsunami-induced forces.

**Keywords:** Tsunami bore, Bed Shear Stress, Wet-Bed Conditions, Laboratory Experiments, Sediment Transport, Hydrodynamic Forces

## 1 Introduction

Tsunami bores are highly energetic wavefronts that develop as a tsunami wave propagates into shallow waters or transitions from the deep ocean to coastal areas. These

bores generate rapid changes in velocity, turbulence, and flow depth, significantly influencing sediment transport, coastal erosion, and the stability of coastal infrastructure (Barnes et al. 2009; Esteban et al. 2019). It is essential to understand their hydrodynamics, particularly the evolution of bed shear stress ( $\tau_b$ ), a force exerted by flowing water on the seabed. This force controls sediment entrainment, deposition, and erosion, shaping coastal morphology (Howe et al. 2019; Thappeta et al. 2023). Given its role in sediment transport,  $\tau_b$  has been extensively examined through experimental and numerical approaches to predict tsunami-induced sediment movement and erosion potential better (Yamashita et al. 2021).

Numerous studies have examined  $\tau_b$  in different hydrodynamic conditions, such as tsunami-like surges, wave run-up, and swash flows. For instance, Howe et al. (2019) showed how acceleration and deceleration phases affect stress variability by measuring  $\tau_b$  in swash flows over steep slopes. Similar to this, Barnes et al. (2009) examined  $\tau_b$  under breaking tsunami bores and solitary tsunami-type waves, giving data regarding the forces acting on the seabed during high-energy wave events.

Although  $\tau_b$  can be estimated using numerical models, controlled laboratory tests are still necessary to validate these models and capture complex hydrodynamic processes. Wave gauges and electromagnetic velocity meters (EMVs) have been used in a number of experimental investigations to detect free surface elevations and velocity variations in controlled settings. Near-bed velocity oscillations can also be captured by EMVs, which is helpful for calculating  $\tau_b$ .

However, bed roughness affects flow velocity, energy dissipation, and turbulence intensity, all of which have an impact on tsunami bore propagation. According to studies, textured surfaces or granular sands that are rougher increase frictional resistance, which lowers bore velocity and modifies impact forces on coastal structures (Chanson 2006). The effect of bed roughness on tsunami bore propagation and overtopping was investigated by Esteban et al. (2019); they emphasized how differences in roughness affect bore behavior.

Normalizing  $\tau_b$  is an essential parameter in sediment transport studies, particularly in high-energy environments such as tsunami-induced flows. Numerous studies have emphasized how important it is to use a suitable reference  $\tau_b$  for normalization to ensure precise predictions of sediment transport dynamics. Soulsby (1997) emphasized that dimensionless  $\tau_b$ , such as the Shields parameter, provides a standardized measure to compare sediment mobility across different flow conditions. Similarly, van Rijn (2007) demonstrated that normalizing  $\tau_b$  using a critical threshold for sediment motion improves the reliability of sediment transport models in coastal engineering applications. Yeh and Li (2008) discovered that tsunami-induced shear strains are beyond normal coastal conditions in the context of major hydrodynamic events, requiring appropriate normalization to evaluate bed stability and erosion potential. The necessity for a suitable normalization strategy is further supported by laboratory flume tests conducted by Arnason et al. (2009), which demonstrated that peak  $\tau_b$  during a tsunami bore controls sediment mobilization and deposition patterns. These studies underscore that selecting a relevant normalizing  $\tau_b$ , whether based on critical  $\tau_b$ , peak bore-induced stress, or time-averaged stress, is vital for accurate sediment transport modeling in tsunami research.

Furthermore, the Saint-Venant equations that characterize unsteady open-channel flow are used to calculate  $\tau_b$  under varied flow conditions. Several studies have applied

the Saint-Venant framework to assess  $\tau_b$  in high-energy coastal environments. Soulsby (1997) noted that these equations effectively predict flow depth and velocity, which are essential for computing  $\tau_b$  using the depth-slope product approach. Similarly, Chanson (2006) highlighted that the Saint-Venant equations are integral to modeling tsunami surges, where  $\tau_b$  determines sediment transport and scour patterns. Barnes et al. (2009) conducted direct  $\tau_b$  measurements in bore-driven swash and confirmed that the depth-averaged shear stress obtained from the Saint-Venant equations closely matches experimental data. Further, Jiang et al. (2015) applied these equations to analyze tsunami-driven sediment motion, demonstrating their reliability in predicting sediment entrainment thresholds. More recently, Thappeta et al. (2023) used the Saint-Venant equations to compare different methods of  $\tau_b$  estimation in experimental flash flood bores, emphasizing their role in understanding high-velocity, unsteady flows. These studies collectively confirm that the Saint-Venant equations provide a robust theoretical basis for calculating  $\tau_b$  in extreme flow conditions, including those relevant to tsunami bore impact studies.

Based on previous research, we experimentally investigated the evolution of normalized bed shear stress ( $\tau_b^*$ ) induced by tsunami bores using depth-averaged velocity ( $U$ ) and local water depth ( $h$ ) during the propagation of the bore in a controlled laboratory setting. Measurements were collected using electromagnetic velocimeters and wave gauges, and  $\tau_b$  was computed using the Saint-Venant framework, following the methodology outlined by Thappeta et al. (2023) in their flash flood bore study.

While Thappeta's work focused on dry-bed conditions, the present study explores bore evolution over a smooth, wet-bed surface—a setup that reflects more realistic coastal scenarios where pre-inundation commonly occurs. Although previous studies such as Nouri et al. (2010) and Yeh and Li (2008) highlighted the importance of wet-bed conditions, full-scale experimental investigations on tsunami bore dynamics over smooth, submerged beds are still relatively scarce. This study addresses this gap by providing a detailed analysis of wet-bed tsunami bore propagation and associated bed shear stress behavior. Focusing on smooth-bed and wet-bed conditions enhances the relevance of laboratory experiments to real-world situations involving sediment transport and coastal infrastructure impact.

Unlike prior studies that emphasize rough-bed topographies, such as riprap or sediment layers (e.g., Esteban et al., 2020; Wüthrich et al., 2019; Jayaratne et al., 2016; Nielsen, 2018), this study focuses on smooth-bed dynamics, which remain underrepresented in the literature despite their relevance in modeling tsunami-induced sediment transport over paved or artificially armored coasts.

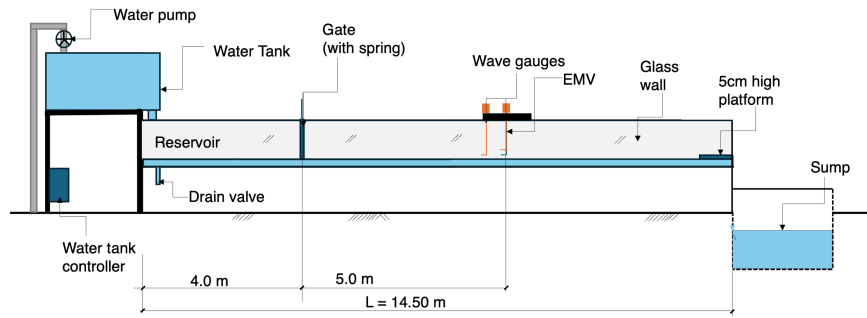
Moreover, to enhance the physical realism of the experiments, wet-bed conditions were used to simulate tsunami bores propagating over shallow water, closely resembling inundation zones observed in coastal plains. As Nouri et al. (2010) emphasized, wet-bed conditions significantly influence flow transition, energy dissipation, and force distribution.

The present work provides new insights by quantifying normalized bed shear stress ( $\tau_b^*$ ) across three dimensionless bore cases ( $H/h_b = 1.4, 2.0, 3.0$ ) and deriving empirical relationships linking normalized peak bed shear stress ( $\tau_{b,p}^*$ ) and depth-averaged velocity ( $U$ ) to dimensionless bore height ( $H/h_b$ ). This study offers practical insights that help predict tsunami-induced forces and addresses a specific gap in existing research. Focusing on smooth-bed and wet-bed conditions enhances the relevance of laboratory

experiments to real-world situations involving sediment transport and coastal infrastructure impact.

## 2 Methodology

### 2.1 Experimental Setup



**Fig. 1** Schematic diagram of the wave flume facility used for the experiments, with a total length of 14.50 m, a width of 0.40 m, and a depth of 0.20 m. The setup includes a spring-loaded vertical lift gate for bore generation, a smooth wet-bed platform 5 cm high, and measurement instrumentation positioned downstream to capture local water depth ( $h$ ) and depth-averaged velocity ( $U$ )

The experiments were carried out in a rectangular wave flume at Kyoto University's Disaster Prevention Research Institute's Ujigawa Open Laboratory. The flume, which is 14.5 m long, 0.4 m wide, and 0.2 m deep, as shown in Figure 1, allows for controlled laboratory simulations of tsunami bores under repeatable conditions. The primary objective of the setup was to investigate bore-induced hydrodynamics over a smooth wet bed, thereby eliminating the influence of bed roughness and allowing a focused examination of tsunami bore fluid dynamics. To enable comparison with larger-scale studies, the present results were normalized and compared against the higher-scale experimental findings of Thappeta et al. (2023).

The dam-break method, originally formulated through theoretical and experimental work by Stoker (1957) and Dressler (1952), is a commonly used technique in wave testing facilities to replicate the sudden surge of water associated with actual tsunami events. This classical approach involves the sudden release of water from a reservoir to simulate unsteady, high-energy flows similar to those generated during tsunami inundation.

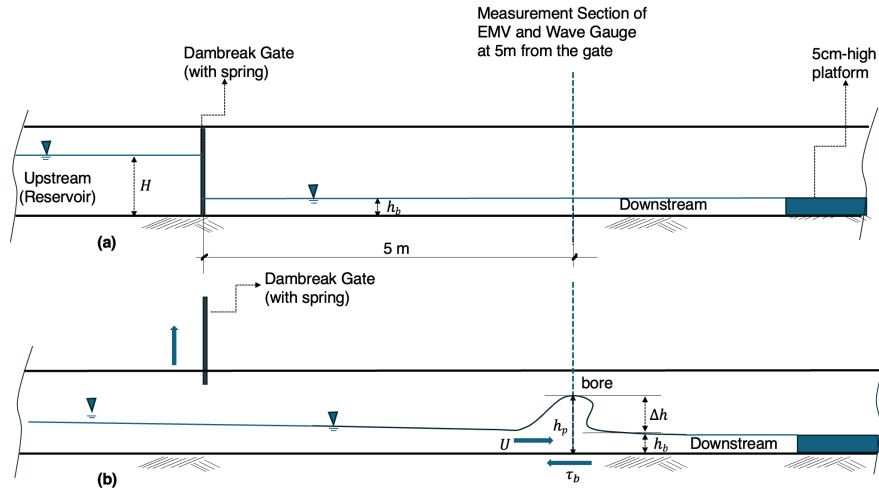
This study employed a spring-loaded vertical lift gate to discharge impounded water rapidly into the flume, generating a propagating bore that traveled downstream. To ensure the formation of a sharp bore front, the gate was released nearly instantaneously via a mechanical spring-trigger mechanism, minimizing delay during opening. Gate opening times were measured using a smartphone camera as 0.133 s ( $H = 7$  cm), 0.137

s ( $H = 10$  cm), and 0.153 s ( $H = 15$  cm), corresponding to approximate velocities of 1.50 m/s, 1.46 m/s, and 1.31 m/s over a 0.20 m lift. Assuming uniform motion, the initial accelerations were estimated at 22.6, 21.3, and 17.1 m/s<sup>2</sup>, respectively. These conditions consistently produced a sudden bore front resembling a dam-break, suitable for the experiment.

The upstream reservoir was prefilled to different initial reservoir depths ( $H$ ), as detailed in Table 1, and the gate was lifted rapidly to generate the tsunami bore (Figure 2a). This approach created a sharp leading edge and a high bore front, replicating real-world tsunami hydrodynamics.

A 5 cm-high platform was placed at the downstream side of the flume to maintain a consistent initial reservoir depth ( $H$ ) and ensure that the bore developed under wet-bed conditions. Using wet-bed conditions in bore simulations is important for accurately replicating real tsunami flow behavior. Nouri et al. (2010) demonstrated that including a shallow base water layer better represents the natural conditions found in coastal areas, where water is already present before a tsunami arrives.

In this study, maintaining a consistent wet-bed setup allowed for a controlled and repeatable experimental environment. A smooth bed and a pre-existing water layer enabled clear observation of bore dynamics without the added influence of surface roughness or irregular flow resistance.



**Fig. 2** Measurement Section of EMV and Wave Gauge at 5m from the gate: (a) Schematic showing the initial upstream reservoir depth ( $H$ ) and the base water depth ( $h_b$ ) under wet-bed conditions at the downstream measurement location. (b) Illustration of the spring-loaded vertical lift gate and the resulting bore propagation from upstream to downstream. Measurement points include the recording of the depth-averaged velocity ( $U$ ) and the peak water surface elevation ( $h_p$ ) during the bore event

## 2.2 Test Parameters and Instrumentation

This experiment investigated the hydrodynamics of tsunami bores using three initial reservoir depths ( $H$ ) in the reservoir: 7 cm, 10 cm, and 15 cm. To align with the recommendation of Nouri et al. (2010) regarding the representation of wet-bed conditions in tsunami bore experiments, the present study maintained a constant base water depth of 5 cm across all test cases. The corresponding dimensionless bore height ratios, defined as the initial reservoir depth ( $H$ ) to base water depth ( $h_b$ ) were 1.4, 2.0, and 3.0 for the initial reservoir depths of 7 cm, 10 cm, and 15 cm initial water levels, respectively. Although these values indicate that the incoming bores were considerably higher than the still water depth, the presence of a non-zero-base layer ensured wave propagation occurred over a fully submerged bed, satisfying the general criteria for wet-bed conditions described in previous literature.

Five independent trials were conducted for each initial reservoir depth ( $H$ ) to ensure repeatability and data reliability. Following the methodology outlined by Chanson and Docherty (2012), local water depth ( $h$ ) and velocity ( $U$ ) measurements were averaged over multiple runs conducted under identical flow conditions to minimize noise and enhance the accuracy of the results.

All raw measurements were initially subjected to a preliminary visual inspection to identify and exclude any erroneous peaks, dropouts, or sensor anomalies. Time series data were recorded for each run using electromagnetic velocimeters (EMVs) and wave gauges installed at fixed points along the flume. Before averaging, a 3-point moving average filter was applied to each time series to reduce high-frequency noise while preserving essential signal features. Although no automated outlier rejection algorithms, such as Grubbs' test, were applied, spurious values deviating from expected trends were manually discarded. The final values for each variable, including  $U$  and  $h$ , were calculated as the average of five valid trials.

The parameters measured in this study were  $h$  and  $U$ , which were used to compute  $\tau_b$  using the Saint-Venant equation. The calculations leveraged the recorded values of  $h$  and  $U$  to estimate  $\tau_b$  dynamics during tsunami bore propagation. Hydrodynamic measurements were collected using electromagnetic velocimeters (EMVs) and capacitance-type wave gauges, both installed at a fixed location 5 m downstream from the gate (Figure 2b) to ensure the bore was fully developed before data collection. This positioning minimized the influence of initial wave formation instabilities and captured a consistent, steady bore profile.

Velocity measurements were made using a Kenek VM-801HN two-dimensional electromagnetic current meter fitted with a VMT2-200-04P probe specifically designed for hydraulic wave experiments. Measurements were taken at multiple vertical positions relative to the bed, as detailed in Table 1, with a particular focus on the near-bed region by positioning the probe 5 mm above the flume bed. The probe was mounted along the centerline of the 0.40-meter-wide flume, ensuring a 20 cm clearance from each sidewall to minimize wall-induced electromagnetic interference (Chanson, 2004).

The EMV has a velocity resolution of 0.001 m/s, a measurement accuracy of  $\pm 2\%$  of full scale, and a response time of 0.05 seconds, making it suitable for resolving rapid

flow transitions induced by tsunami-like bores. The device was calibrated per the manufacturer's specifications before data acquisition to ensure measurement reliability.

Simultaneously, local water depth ( $h$ ) was recorded using a Kenek capacitance-type wave height meter placed adjacent to the EMV probe at the 5-meter downstream location. The gauge provided surface elevation measurements with an accuracy of  $\pm 1$  mm and a vertical resolution of 0.1 mm. The device was connected to a Graphtech made midi logger GL240, operating at a sampling frequency of 10 Hz, sufficient to capture the transient fluctuations associated with bore propagation.

All velocity and depth data were synchronized and recorded through a high-frequency digital acquisition system. Prior to experimental runs, the flume was fully calibrated, including the verification of instrument response, wave gauge sensitivity, and EMV accuracy under controlled steady flow conditions.

This careful calibration and measurement process ensured that the collected data reliably represented the hydrodynamic behavior of the tsunami bores while minimizing errors and improving the consistency of the experimental results.

**Table 1.** Experimental conditions for tsunami bore propagation over a wet bed with a base depth of  $h_b = 5.2$  cm.

| Initial reservoir depth, $H$ (cm) | Distance from the gate (m) | Height of EMV above the bed, $y$ (cm) |
|-----------------------------------|----------------------------|---------------------------------------|
| 7                                 | 5                          | 0.50,1.0,2.0,3.0,4.0                  |
| 10                                | 5                          | 0.50,1.0,2.0,3.0,4.0                  |
| 15                                | 5                          | 0.50,1.0,2.0,3.0,4.0                  |

### 2.3 Calculation of Bed Shear Stress Using Saint-Venant Equation

Accurately calculating bed shear stress ( $\tau_b$ ) in tsunami bore-induced flows is challenging due to the highly dynamic and unsteady nature of the flow field. The rapidly changing hydrograph, characterized by abrupt variations in flow velocity ( $U$ ) and local water depth ( $h$ ), adds complexity to the estimation process.

Thappeta et al. (2023) applied the Saint-Venant equations to this problem and concluded that this method provides the most reliable method of estimating  $\tau_b$  under such unsteady flow conditions.

The Saint-Venant equations, which govern unsteady open-channel flows, are derived from the Navier-Stokes equations under the assumption that vertical velocity variations are much smaller than horizontal ones (Chaudhry 2008). These depth-averaged equations allow for practical estimation of  $\tau_b$  by simplifying the governing equations while preserving essential flow dynamics. Since hydrodynamic forces are necessary for seabed erosion, coastal sediment transport, and other geomorphological processes, an accurate estimate of  $\tau_b$  is essential to understanding the forces acting on the seabed during tsunami bore propagation (Chaudhry 2008; Dey 2014).

In this study,  $\tau_b$  was computed using the Saint-Venant equation, an established approach in fluid mechanics for analyzing unsteady open-channel flows (Thappeta et al., 2023). The bed shear stress ( $\tau_b$ ) was calculated using the relation:

$$\tau_b = |\gamma R S_f|; \quad (1)$$

where  $\tau_b$  = bed shear stress (Pa),  $\gamma$  = specific weight of water (N/m<sup>3</sup>),  $R$  = hydraulic radius (m),  $S_f$  = friction slope.

The friction slope ( $S_f$ ) was estimated based on the depth-averaged Saint-Venant momentum equation:

$$S_f = S_o + \frac{U}{gh} \frac{\partial h}{\partial t} + \left( \frac{U^2}{gh} - 1 \right) \frac{\partial h}{\partial t} - \frac{1}{g} \frac{U}{gh} \quad (2)$$

where  $S_o$  = longitudinal slope,  $U$  = depth-averaged velocity (m/s),  $g$  = acceleration due to gravity (m/s<sup>2</sup>),  $h$  = local water depth (m),  $t$  = time (s).

To facilitate comparison across different bore cases, the normalized peak bed shear stress ( $\tau_{b,p}^*$ ) was calculated as follows:

$$\tau_{b,p}^* = \tau_{b,p} / (\rho g \Delta h + \rho U^2) \quad (3)$$

where  $\Delta h = h_p - h_b$  (m) represents the difference between the peak ( $h_p$ ) and base ( $h_b$ ) water depths during bore propagation,  $\tau_{b,p}$  = Peak bed shear stress (Pa),  $\rho$  = density of water (kg/m<sup>3</sup>), and  $U$  = depth-averaged velocity (m/s).

By applying this approach, the study ensures a systematic and physically consistent method for evaluating the forces acting on the seabed during tsunami bore events.

### 3 Results and Discussion

#### 3.1 Relationship Between Local Water Depth ( $h$ ) and Depth-Averaged Velocity ( $U$ ) in Tsunami Bore Flows

One important measure of bore intensity is the depth-averaged velocity ( $U$ ), which affects flow momentum, turbulence, and hydrodynamic behavior (Chanson 2006; Stoker 1957). Understanding the relationship between local water depth ( $h$ ) and velocity ( $U$ ) is essential to understanding energy transfer caused by tsunami bores. According to Fritz et al. (2004), examining velocity changes at various  $h$  gives information about the distribution of energy and the interactions between the bore and its environment and the seabed. This relationship has been further supported by experimental research. The findings of Masaya et al. (2020) indicate that larger bores generate higher velocities, leading to greater turbulence and more efficient energy transfer.

Figure 3 presents the time histories of (a) local water depth ( $h$ ) and (b) depth-averaged velocity ( $U$ ) measured 5 meters downstream from the gate for initial reservoir depths of  $H = 7$  cm, 10 cm, and 15 cm. The time series captures the full evolution of flow during bore propagation, from the arrival of the leading edge to the post-peak stabilization phase.

In all cases, the arrival of the bore caused a sharp rise in both water depth and velocity, followed by a gradual decline as the flow transitioned toward steady conditions. Larger initial reservoir depths, particularly  $H = 15$  cm, resulted in steeper bore fronts, higher peak values, and higher post-peak oscillations than smaller bores. These oscillations are attributed to reflected backflow effects induced by the 5 cm-high downstream platform, which generated secondary wave activity after the bore impact.

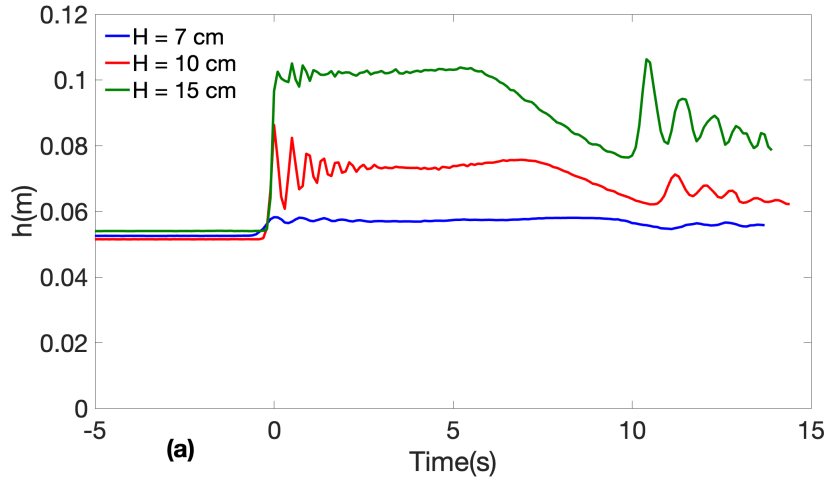
Meanwhile, the results confirm this trend, showing that  $U$  increased with  $h$ , indicating that larger bores carry more energy, as illustrated in Figure 3. For an initial reservoir

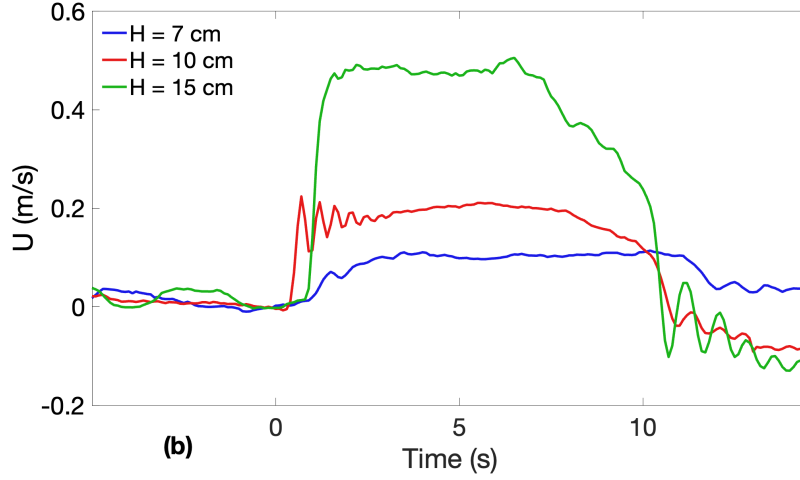
depth of  $H = 7$  cm, the peak depth-averaged velocity ( $U_{max}$ ) was 0.114 m/s. This value increased to 0.224 m/s for  $H = 10$  cm and reached 0.505 m/s for  $H = 15$  cm

The time series shown in Figure 3 represents the averaged results from five repeated experimental runs under identical initial and boundary conditions. Prior to averaging, the raw signals were visually inspected to remove spurious peaks, and a 3-point moving average was applied to minimize high-frequency noise while preserving the physical trends. This approach ensures that the presented profiles accurately capture the typical bore behavior, minimizing the effects of random variability across individual trials.

These results align with Stoker (1957), who demonstrated that deeper flows correspond to greater momentum and enhanced gravitational potential energy. The increasing trend in  $U_{max}$  suggests that higher bores lead to stronger flow inertia, contributing to greater sediment transport potential and higher  $\tau_b$  levels.

The observed scaling relationship between local water depth ( $h$ ) and velocity ( $U$ ) underscores the importance of bore height in shaping tsunami-driven hydrodynamics. It reinforces its importance in predicting energy transfer and sediment movement during such events.





**Fig. 3** Time histories of (a) local water depth ( $h$ ) and (b) depth-averaged velocity ( $U$ ) measured 5 meters downstream from the gate for initial reservoir depths of  $H = 7$  cm, 10 cm, and 15 cm. The arrival of the tsunami bore was identified as the point at which the water surface elevation first exceeded 2 mm above the base water level ( $h_b = 0.052$  m), providing a consistent reference for  $T = 0$  across all cases. The plots illustrate the rapid rise in both  $h$  and  $U$  upon bore front arrival, followed by gradual stabilization. Larger bores exhibit higher peak values and more pronounced post-peak oscillations than smaller bores. These oscillations are attributed to reflected flow effects caused by the 5 cm-high downstream platform, which caused flow reversal after the bore front passed. The results emphasize the role of bore height and bed topography in shaping the temporal evolution of tsunami-induced hydrodynamic forces

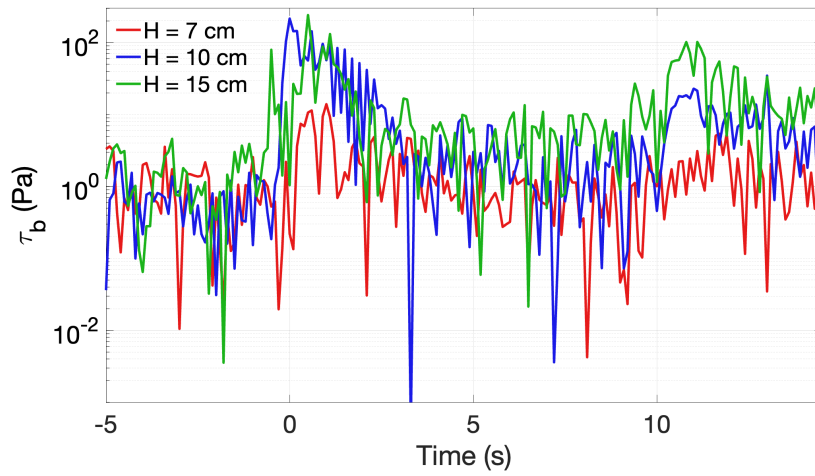
### 3.2 Bed Shear Stress ( $\tau_b$ )

Bed shear stress plays a fundamental role in sediment transport processes, influencing erosion, deposition, and coastal morphology. The interaction between bore-driven hydrodynamics and the seabed exerts varying degrees of  $\tau_b$ , which dictates sediment mobilization in a tsunami-bore-induced flow. Understanding the temporal evolution of  $\tau_b$  is crucial for predicting sediment transport patterns and assessing the potential impacts of tsunami-induced scour on coastal infrastructure (Chanson & Docherty 2012).

Figure 4 shows the time series of the calculated bed shear stress ( $\tau_b$ ) based on the Saint-Venant equations, using the data measured 5 meters downstream from the dam-break gate for initial reservoir depths of  $H = 7$  cm, 10 cm, and 15 cm. The peak bed shear stress values ( $\tau_{b,p}$ ) were determined as 13.95 Pa, 216.21 Pa, and 242.00 Pa for  $H = 7$  cm, 10 cm, and 15 cm, respectively. These results confirm that larger bores generate higher shear stress due to the increased flow momentum and energy associated with greater bore heights.

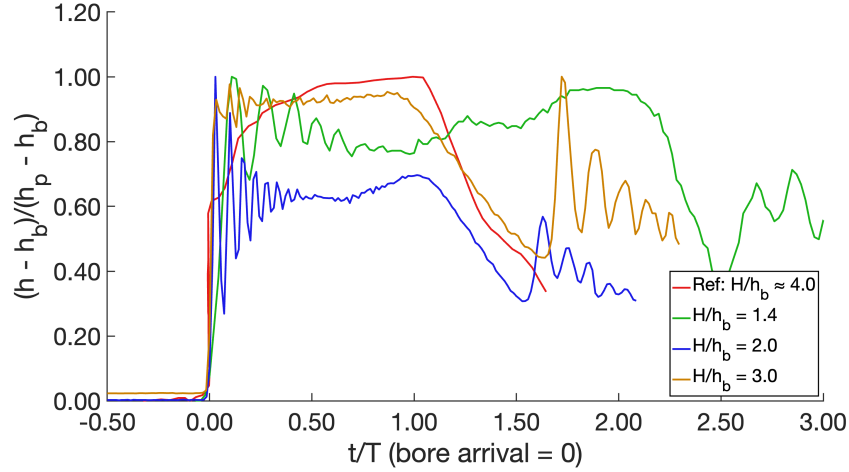
After reaching peak values,  $\tau_b$  dropped rapidly, indicating energy redistribution as the bore expanded and flow turbulence diminished. This decline reflects the transition from a high-energy front to a more uniform, slower-moving flow. Such behavior highlights the dynamic response of  $\tau_b$  during tsunami bore passage. Initially, elevated shear forces are present, which promote sediment mobilization; however, the following reduction in stress determines whether that sediment settles or continues to move within the flow (Chanson & Docherty, 2012).

Careful monitoring of  $\tau_b$  evolution is essential for understanding the early-stage erosive forces and the longer-term sediment transport effects of tsunami bores.



**Fig. 4** Time series of bed shear stress ( $\tau_b$ ) for initial reservoir depths of  $H = 7$  cm, 10 cm, and 15 cm, measured 5 meters downstream from the dam-break gate. The plots show the evolution of  $\tau_b$  following bore arrival, highlighting differences in peak stress magnitude and post-peak fluctuations across varying bore intensities. Larger bores (e.g.,  $H = 15$  cm) exhibit higher peak shear stresses and more pronounced oscillations, while smaller bores stabilize faster with lower shear stress amplitudes

### 3.3 Normalized Water Depth Evolution



**Fig. 5** Time series of normalized water depth  $(h - h_b)/(h_p - h_b)$  for initial reservoir depths of  $H = 7$  cm, 10 cm, and 15 cm, together with the reference profile (red line) from Thappeta et al. (2023). The plots show the evolution of the water surface relative to the full bore rise, with time normalized by bore arrival time ( $t/T$ ). The present study features finite dimensionless bore height ratios ( $H/h_b = 1.4, 2.0$ , and  $3.0$ ), while the reference case represents a dry-bed regime ( $H/h_b \rightarrow \infty$ ). The bore arrival time ( $t/T = 0$ ) is defined as the moment when the surface elevation exceeds 2 mm above the base level  $h_b = 0.052$  m. The comparison is presented solely to illustrate qualitative similarity in bore development, not as a validation across regimes

Figure 5 presents the evolution of normalized water depth  $(h - h_b)/(h_p - h_b)$  over dimensionless time ( $t/T$ ), enabling a comparative assessment of tsunami bore evolution for different initial reservoir depths ( $H$ ). The dataset comprises initial reservoir depth ( $H$ ) of 7 cm, 10 cm, and 15 cm, alongside a reference dataset (red line) from Thappeta et al. (2023). This analysis highlights variations in bore front behavior, peak depth, and flow stabilization patterns across different bore conditions.

At  $t/T = 0$ , all cases exhibit a sharp increase in normalized water depth, signifying the arrival of the tsunami bore front. This abrupt rise is a defining characteristic of tsunami bores, where the leading wave rapidly transfers energy to the fluid domain, causing an almost instantaneous surge in water depth. The steeper initial rise observed in the 10 cm and 15 cm bores (blue and orange lines, respectively) suggests that higher initial bore depths lead to higher bore propagation.

It is important to note that the reference dataset from Thappeta et al. (2023) was generated under dry-bed conditions—that is, with no pre-existing water depth ( $h_b = 0$ , or  $H/h_b \rightarrow \infty$ ). In contrast, the present study was conducted under wet-bed conditions, using controlled and physically representative base depths of 5.2 cm, resulting in finite  $H/h_b$  ratios of 1.4, 2.0, and 3.0. These two regimes exhibit fundamentally different bore dynamics; therefore, the comparison with Thappeta et al. (2023) is provided solely for qualitative insight, not as a direct benchmark for validation.

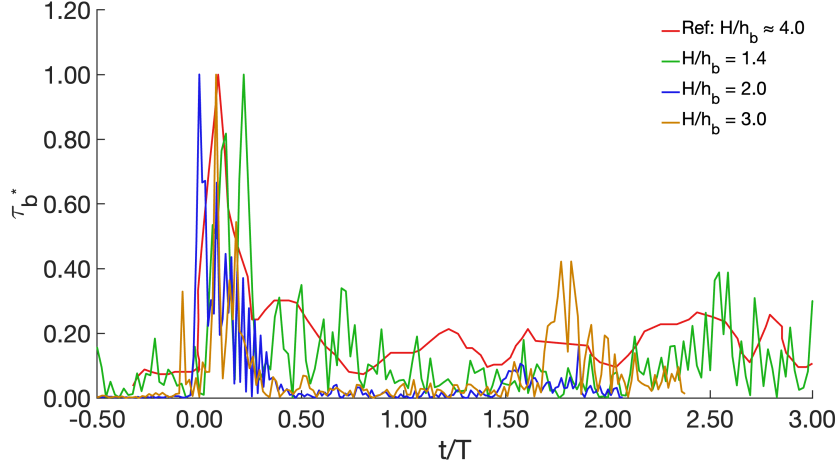
The peak normalized water depth varies significantly across different cases. The  $H = 15$  cm bore attains the highest peak (Figure 4), indicating a stronger surge with higher energy content. In contrast, the  $H = 10$  cm bore reaches its peak more gradually and stabilizes faster, suggesting a more uniform energy distribution. The  $H = 7$  cm bore (green line) shows the most moderate increase and stabilization, indicating that smaller bores result in smoother, less energetic propagation.

These trends are not only a function of bore height but are also influenced by the dimensionless bore height ( $H/h_b$ ), which governs the hydrodynamic behavior after the bore peak. In the present experiments, the lower  $H/h_b$  ratios (1.4, 2.0, and 3.0) contribute to more subdued post-peak fluctuations. In contrast, the reference case by Thappeta et al. (2023), with a higher  $H/h_b$  ratio of approximately 4, exhibits sharper post-peak transitions—supporting the view that larger dimensionless depths enhance flow inertia and prolong flow recovery. This observation aligns with established hydrodynamic principles, wherein increased bore strength correlates with greater momentum and extended wave influence (Chanson & Docherty, 2012).

Comparing these results with the reference study by Thappeta et al. (2023) (red line), a qualitative similarity is observed in bore initiation and peak development, affirming the reliability of the present experimental setup. However, slight deviations in post-peak behavior suggest possible differences in experimental conditions, such as bore generation techniques, bed wetness (dry vs. wet beds) or channel roughness, which influence the rate of flow stabilization. The clear agreement in bore front dynamics and peak behavior confirms the robustness of the present methodology in capturing tsunami bore evolution.

These findings reinforce the role of dimensionless bore height ( $H/h_b$ ) in governing energy transfer, flow momentum, and bore stabilization. Higher bores result in more intense energy surges that drive rapid bore development but require longer periods to stabilize. In contrast, intermediate bores such as  $H = 10$  cm demonstrate a more balanced progression, suggesting favorable conditions for controlled and steady propagation. Further comparison with a broader set of large-scale experiments under consistent boundary conditions would strengthen these interpretations.

### 3.4 Normalized Bed Shear Stress Evolution



**Fig. 6** Comparison of normalized bed shear stress ( $\tau_b^*$ ) over dimensionless time ( $t/T$ ) for various bore conditions  $H/h_b = 1.4$  (green),  $2.0$  (blue), and  $3.0$  (orange), with a reference data set (red) representing  $H/h_b \approx 4.0$  from Thappeta et al. (2023). Time denotes the instant of peak bed shear stress  $\tau_{b,p}$ . The plot highlights the temporal evolution of near-bed shear under different dimensionless bore height ratios

Figure 6 presents the temporal evolution of normalized bed shear stress  $\tau_b^*$  over dimensionless time ( $t/T$ ), enabling a comparative analysis of  $\tau_b$  evolution across different bore intensities. The plot includes bore cases with different initial reservoir depths ( $H$ ) of 7 cm, 10 cm, and 15 cm alongside a reference profile (red line) from Thappeta et al. (2023), which serves as a comparative benchmark.

The results demonstrate a clear correlation between bore height and peak bed shear stress ( $\tau_{b,p}$ ), confirming the expectation that larger bores generate higher  $\tau_b$  due to increased flow momentum and near-bed turbulence. As shown in Figure 4, the  $H = 15$  cm bore (orange line) exhibited the highest  $\tau_{b,p}$ , followed by  $H = 10$  cm (blue) and  $H = 7$  cm (green). This trend aligns with the fundamental principles of hydrodynamics, where greater bore heights correspond to higher velocity gradients and stronger bed interactions.

Following the peak, all cases exhibit distinct fluctuations in  $\tau_b$ , reflecting the highly turbulent nature of bore-induced flows. Notably, the  $H = 15$  cm bore displays more pronounced oscillations, suggesting the presence of amplified turbulent bursts and vortex shedding, which significantly modulate bed stress dynamics over time. Conversely, the  $H = 7$  cm bore stabilizes more quickly, indicating that smaller bores result in faster stabilization and smoother shear stress decay. This behavior suggests that lower energy flows lead to more consistent  $\tau_b$  patterns, while larger bores introduce greater variability due to turbulence and energy dissipation effects.

A comparison with the Thappeta et al. (2023) dataset (red line) reveals similar trends in  $\tau_{b,p}$  formation, confirming the consistency and reliability of the present experimental

setup within the tested conditions. However, slight differences in post-peak behavior can be attributed to variations in experimental conditions, such as bed wetness and bore generation technique, and channel configuration.

To better understand the observed trends, it is necessary to explain the differences between the present wet-bed experiments and the dry-bed reference study, particularly focusing on the early stages of bore development.

Although the present wet-bed experiments show general agreement with the dry-bed reference data from Thappeta et al. (2023), closer inspection reveals discrepancies both before and after the peak. Differences in the pre-peak behavior can be attributed to several factors. First, the presence of an initial water layer ( $h_b = 5.2$  cm) in the present experiments modifies the bore dynamics, producing a more gradual steepening of the bore front compared to the sharper surge observed in dry-bed conditions. This smoother transition delays the acceleration of flow velocity and bed shear stress in the early phase. Second, differences in the gate release mechanisms, with a spring-loaded lift gate used in this study versus a sudden drop gate in Thappeta et al. (2023), may have introduced slight variations in the initial bore formation. Finally, differences in experimental scale, downstream boundary conditions, and flume geometry could also contribute to early-stage flow evolution discrepancies. These factors highlight the sensitivity of bore hydrodynamics to the experimental setup and emphasize the need for careful interpretation when comparing across different boundary conditions.

Despite these differences, the overall similarity in bore front development and the consistent trends observed in normalized bed shear stress confirm the reliability of the present experimental setup for capturing key tsunami bore hydrodynamic characteristics.

Overall, these results emphasize that bed shear stress dynamics are strongly dependent on bore height. Larger bores not only elevate peak shear forces but also increase the temporal variability of shear stress due to intensified turbulence following bore impact.

### 3.5 Normalized Peak Bed Shear Stress ( $\tau_{b,p}^*$ ) and Bore Height Relationship

The peak bed shear stress ( $\tau_{b,p}$ ) was normalized using the dimensionless parameter  $\tau_{b,p}^* = \tau_{b,p} / (\rho g \Delta h + \rho U^2)$ . This normalization provides a dimensionless representation of the stress exerted on the seabed, allowing for direct comparisons across different bore conditions.

This study examined the relationship between normalized peak bed shear stress ( $\tau_{b,p}^*$ ) and the dimensionless bore height ( $H/h_b$ ) to evaluate the efficiency of energy transfer from the bore to the seabed. The results show a nonlinear trend, confirming that bore strength significantly influences bed stress response. As illustrated in Figure 7a, an exponential relationship provided the best fit to the data:

$$\tau_{b,p}^* = 0.208 \cdot e^{0.270(H/h_b)} \quad (R^2 = 0.95) \quad (4)$$

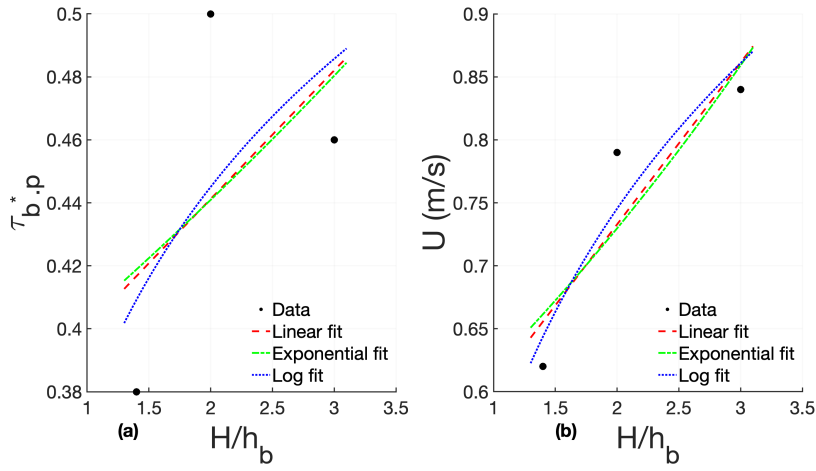
This finding highlights that even modest increases in  $H/h_b$  can cause disproportionately higher stress values on the seabed, enhancing sediment mobilization potential.

Similarly, the depth-averaged velocity ( $U$ ) showed a strong linear relationship with dimensionless bore height ( $H/h_b$ ), as shown in Figure 7b:

$$U = 0.133(H/h_b) + 0.433 \quad (R^2 = 0.97) \quad (5)$$

This relationship suggests a more proportional increase in mean flow speed.

To provide a more statistically robust interpretation, uncertainty analysis was conducted. The average normalized peak bed shear stress across all conditions was 0.50, with a standard deviation (SD) of  $\pm 0.04$ . This metric reflects the variability arising from repeated experiments and accounts for experimental noise, sensor resolution, and bore generation irregularities. These empirical trends and uncertainty metrics were used to refine the interpretation of bore behavior and enhance the analysis presented in Figure 8.

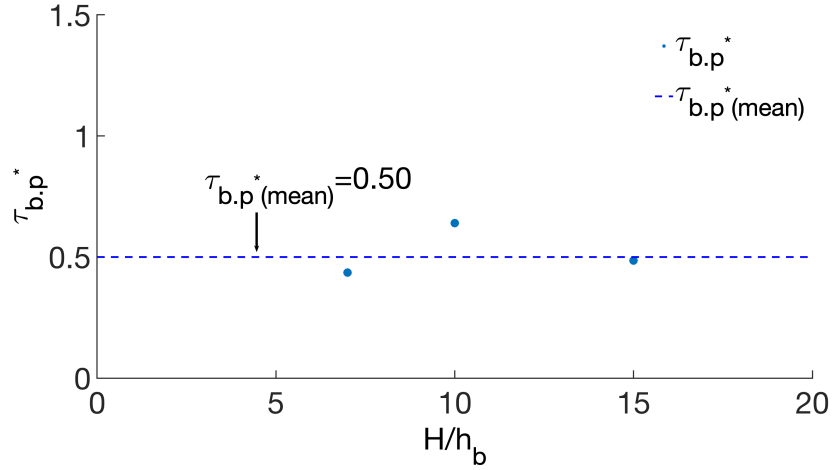


**Fig 7.** (a) Variation of normalized peak bed shear stress ( $\tau_{b,p}^*$ ) and (b) depth-averaged velocity ( $U$ ) as a function of the dimensionless bore height ( $H/h_b$ ). The plots compare experimental data (black dots) with three fitted models: linear (red dashed line), exponential (green dash-dotted line), and logarithmic (blue dotted line). The exponential fit shows the best agreement in panel (a), while the linear fit aligns closely with the velocity trend in panel (b), highlighting the relationship between bore intensity and hydrodynamic response

As shown in Figure 8,  $\tau_{b,p}^*$  reached its maximum at  $H = 10$  cm with  $\tau_{b,p}^* = 0.640$ . In contrast, at lower bore depths ( $H = 7$  cm), the  $\tau_{b,p}^*$  was reduced ( $\tau_{b,p}^* = 0.360$ ), likely due to the limited energy transfer from the bore to the bed. For higher bore depths ( $H = 15$  cm,  $\tau_{b,p}^* = 0.485$ ), energy transfer efficiency appears to decrease, possibly due to energy dispersion and turbulence effects, which reduce the net force acting on the seabed.

The mean normalized shear stress value  $\tau_{b,p}^*(mean) = 0.50$  serves as a baseline for evaluating deviations in bore-induced  $\tau_b$  across different cases. These findings suggest that moderate bore heights optimize energy transfer efficiency, while both lower and higher bores exhibit reduced  $\tau_b$  due to energy limitations or dispersion effects. This aligns with prior research, which indicates that bore-induced turbulence and wave-breaking dynamics influence  $\tau_b$  and sediment transport (Chanson 2004).

The observed trend underscores the importance of bore height selection in experimental and numerical modeling to achieve realistic  $\tau_b$  estimations for coastal hazard assessments and sediment transport simulations.



**Fig. 8** Plot illustrating the relationship between normalized peak bed shear stress ( $\tau_{b,p}^*$ ) and dimensionless bore height ( $H/h_b$ ). Each data point corresponds to the average  $\tau_{b,p}^*$  derived from five independent experimental runs conducted under identical conditions for each initial reservoir depth ( $H = 7, 10$ , and  $15$  cm), corresponding to  $H/h_b$  ratios of 1.4, 2.0, and 3.0, respectively. This averaging was intended to minimize variability and enhance the robustness of the observed trend. The dashed line represents the mean normalized peak shear stress  $\tau_{b,p}^*(mean) = 0.50$ , with standard deviation  $\pm 0.04$ , showing trends across different bore intensities

## 4 Conclusions

This study investigated the dynamics of normalized mean peak bed shear stress  $\tau_{b,p}^*(mean) = 0.50$  induced by tsunami bores over a smooth bed. The results demonstrated a clear correlation between local water depth ( $h$ ), bed shear stress ( $\tau_b$ ), and depth-averaged velocity ( $U$ ), confirming that larger bores generate higher energy levels and turbulence.

However, the observed nonlinear trend in normalized peak bed shear stress ( $\tau_{b,p}^*$ ) highlights the importance of moderate bore height, particularly within the dimensionless range of  $1.4 \leq H/h_b \leq 3.0$ , for achieving optimal energy transfer to the bed. While the present experiments captured essential trends within this range, it is acknowledged that this represents a relatively narrow spectrum. Further investigations spanning a broader range of relative bore heights are recommended to generalize the findings to more extreme tsunami conditions. Moderate  $H/h_b$  values facilitated efficient momen-

tum transfer to the seabed, whereas larger relative bore heights produced higher absolute bed shear stress ( $\tau_b$ ), but exhibited diminished efficiency due to enhanced turbulence and energy dispersion. This observation suggests the existence of different regimes of energy transfer based on  $H / h_b$ , where moderate values favor bed loading and larger values favor turbulent energy dissipation.

The analysis of normalized water depth evolution supported this finding by showing that larger bores caused more pronounced oscillations and longer periods of turbulence, leading to less stable flow conditions.

When compared with the dry-bed reference study by Thappeta et al. (2023), our results showed consistent trends in bore development but notable differences in post-peak behavior. These deviations underscore the influence of boundary conditions, such as bed wetness and bore generation methods, on bed shear stress ( $\tau_b$ ) dynamics. This highlights the need for additional studies under broader  $H / h_b$  conditions and varied physical configurations to better understand scaling effects.

These findings have significant implications for tsunami-induced sediment transport and coastal engineering applications. Understanding how bore height affects energy distribution, turbulence intensity, and bed shear stress ( $\tau_b$ ) fluctuations over time is critical for predicting sediment mobilization, erosion patterns, and seabed stability. This study emphasizes the importance of moderate bore depths in balancing hydrodynamic forces on the seabed while ensuring efficient energy transfer and dissipation. The insights gained contribute to improving numerical models, enhancing coastal hazard assessments, and guiding the design of tsunami-resilient coastal defenses.

Future research should explore the effects of sediment transport thresholds and bore-bed interactions under varying flow conditions to further refine predictive models and enhance the understanding of tsunami-driven hydrodynamics in natural coastal environments. These findings can, in particular, directly inform the design of tsunami-resilient coastal structures and support improved predictions of seabed erosion under extreme wave conditions.

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