Experimental study on normalized bed shear stress of tsunami bore

○Charles MATEO, Michio SANJOU, Tsutomu MIURA, Mikihiro NAKAMOTO

This study investigates the normalized bed shear stress ($\tau_{b.p}$) induced by tsunami bores over a smooth bed surface, focusing on the relationship between initial water depth (*H*), bore height, and depth-averaged velocity (*U*). The dam-break method was used in a wave testing facility to model tsunami bores with initial water depths of 7 cm, 10 cm, and 15 cm. The bed shear stress was estimated using the Saint-Venant formula and normalized against a calculated baseline value of $\tau_{b.p}/\rho g\Delta h = 0.520$. The results showed that shear stress and depth-averaged velocity increased dramatically with *H*, reflecting greater energy and turbulence with larger bores. These findings provide baseline data for tsunami bore behavior and coastal infrastructure design to mitigate hydrodynamic forces.

1. Introduction

Tsunami bores are powerful hydrodynamic events that generate significant bed shear stresses, influencing sediment transport, coastal erosion, and the stability of infrastructure (Chanson, 2006). Their turbulent and unsteady nature sets them apart from typical open-channel flows, requiring focused study to accurately predict erosion and design effective coastal defenses. Understanding bed shear stress (τ_b) is essential for assessing these impacts under extreme hydrodynamic conditions.

Previous studies, such as those by Brocchini and Peregrine (2001), have highlighted the importance of bore height and velocity in influencing bed stresses. However, the normalized bed shear stress ($\tau_{b.p}/\rho g\Delta h$), a key parameter for comparing forces across varying conditions, remains underexplored. Most research has focused on rough beds, leaving smooth bed dynamics largely unexamined. This study addresses these gaps through controlled experiments, quantifying normalized bed shear stress, and identifying trends to guide coastal defense design and can be applied to predict coastal sediment transport and erosion patterns. The average normalized value, $\tau_{b.p}/\rho g\Delta h = 0.520$, provides a baseline for comparing bore-induced stresses in different scenarios.

2. Methodology

2.1 Experimental Setup

The experiments were conducted in a rectangular wave testing facility measuring 14.5 m long, 0.4 m wide, and 0.2 m deep. The flume's bed was smooth and focused solely on bore-induced hydrodynamics. Tsunami bores were generated using a dam-break method by releasing a vertical gate to create a sudden surge of water downstream. Measurements were taken at *x*=5m downstream of the gate.

2.2 Test Parameters

Three initial water depths (*H*)—7 cm, 10 cm, and 15 cm—were tested, with five trials conducted for each depth. The key parameters measured included water depth (*h*), depth-averaged velocity (*U*), and bed shear stress (τ_b). Depth-averaged velocity was captured using an Electromagnetic Velocimeter (EMV), and water depth was recorded using wave gauges.

2.3 Calculation of Bed Shear Stress

Bed shear stress (τ_b) was estimated using the Saint-Venant formula (Thappeta et al., 2023):

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

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

where τ_b= bed shear stress (Pa), γ = specific weight of water (N/m^3), R= hydraulic radius (*m*), S_f = friction slope, S_o = longitudinal slope, V = depth-averaged velocity (m/s), g = acceleration due to gravity (m/s^2), *h* = water depth (*m*), *t* = time (*s*).

Normalized bed shear stress was calculated as:

$$\tau_b^* = \tau_b/\rho g\Delta h \quad (3)$$

where $\Delta h = h_p - h_b$ represents the difference between the peak (h_p) and base (h_b) water depths during bore propagation.

3. Results and Discussion

3.1 Depth-Averaged Velocity (*U*)

The depth-averaged velocity increased with initial water depth, reflecting the more significant energy with larger bores. For H=7cm, the peak depth-averaged velocity (U_{max}) was 0.114 m/s. This increased to 0.224 m/s for H=10 cm and 0.505 m/s for H=15cm. Larger bores also showed strong changes in velocity, which means there was more turbulence. These trends align with theoretical predictions (Stoker, 1957), which suggest that larger depths correspond to greater flow momentum and gravitational potential energy.

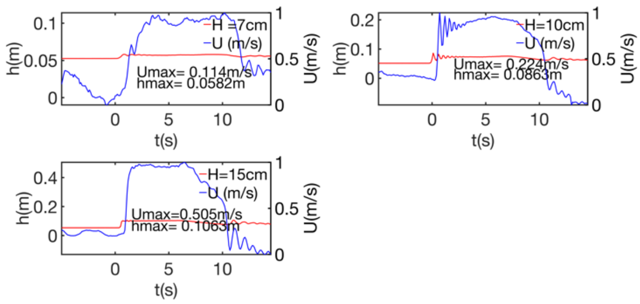

Figure 1. Depth-averaged velocity time series for different H

3.2 Bed Shear Stress (τ_b)

Figure 2 shows the temporal evolution of bed shear stress (τ_b) and water depth (h) for H=7cm,10cm, and 15cm. Peak shear stress increases with H, reaching 13.95Pa, 216.21Pa, and 242.00Pa, respectively, corresponding to peak water depths of h_{max} =0.0582m, 0.0863m, and 0.1063m. After each peak, there was a sudden drop in shear stress. This was caused by energy being redistributed and velocity gradients becoming less steep as the bore changed into a wider, less turbulent flow. These findings emphasize the dynamic nature of bore-induced stresses and align with previous studies (Chanson, 2006).

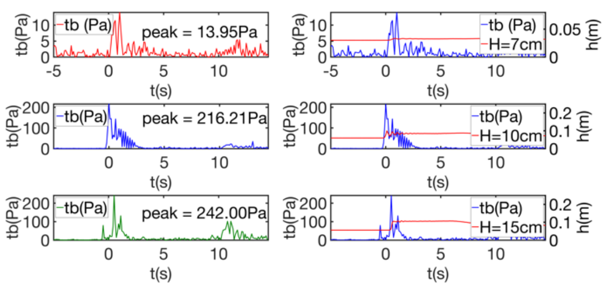

Figure 2. Temporal evolution of bed shear stress for different H

3.3 Normalized Peak Bed Shear Stress ($\tau_{b.p}$)

The normalized peak bed shear stress ($\tau_{b.p}/\rho g\Delta h$) followed a parabolic trend as shown in Figure 3, peaking at H=10cm with $\tau_{b.p}/\rho g\Delta h = 0.640$. Lower depths ($H = 7cm,\ \tau_{b.p}/\rho g\Delta h = 0.435$)) resulted in limited bore energy, while higher depths (H=15cm, $\tau_{b.p}/\rho g\Delta h = 0.485$) exhibited reduced efficiency due to energy dispersion. The average normalized value ($\tau_{b.p}/\rho g\Delta h = 0.520$) serves as a baseline for comparisons. These findings emphasize the importance of moderate depths in optimizing bore energy transfer and align with prior research (Chanson, 2006).

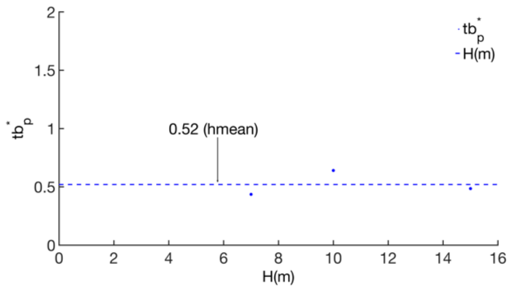

Figure 3. Normalized bed shear stress vs. time for different H

4. Conclusions

This study investigated the normalized peak bed shear stress ($\tau_{b.p}/\rho g\Delta h = 0.52$) induced by tsunami bores over a smooth bed. Results showed that shear stress and depth-averaged velocity increased significantly with H, reflecting larger bores' greater energy and turbulence. The parabolic trend in normalized bed shear stress highlights the importance of moderate bore depths (H=10cm) for efficient energy transfer to the bed. These findings provide a framework for understanding bore dynamics and designing tsunami-resistant coastal defenses.

5. References

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