

Numerical modelling of tsunami propagation in idealised converging channels

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INTRODUCTION

Tsunamis are long gravity waves caused by the displacement of a large volume of water, such as through tectonic movements or landslides. They threaten passing ships, dams and buildings, leading to devastating disasters. The characteristics of tsunamis, such as the wave height, wavelength and direction, are significantly influenced by the geometry of the water body (Ruffini et al., 2019; Chen et al., 2023). Although the 2018 Palu Bay event caused severe damage to Palu City, resulting in over 4,340 fatalities, 4,438 injuries and widespread destruction of the built environment (Goda et al., 2019), little attention has been given to the physics of tsunamis propagating in converging water bodies.

Tsunamis propagating in converging water bodies impact the sidewalls or shores at an oblique angle. So-called Mach reflection may be observed when a solitary wave interacts with a vertical wall at a sufficiently small angle ψ (e.g. $20^\circ \leq \psi \leq 40^\circ$, Li et al., 2011). As shown in Figure 1, this interaction creates a reflected wave that intersects with the incident wave and forms a high-amplitude Mach stem wave perpendicularly to the wall (Miles, 1977; Li et al., 2011). The stem length l_s increases with a gradient indicated by the angle ψ_w as the wave propagates. Whilst l_s increases linearly, the stem wave amplitude a_w does not. The rate at which a_w is amplified decreases, approaching a theoretical asymptotic value as the process continues.

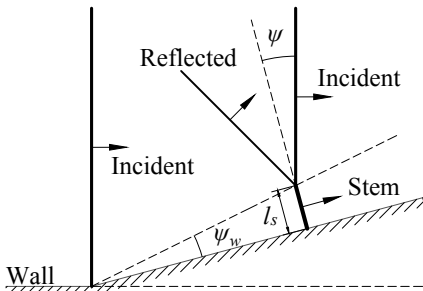


Figure 1. Schematic diagram of an incident solitary wave interacting with the wall obliquely resulting in Mach reflection. The widths of the lines representing the wave crests are indicative of the size of the wave amplitudes.

To gain a deeper understanding of how tsunamis propagate in converging water bodies, Chen et al. (2023) conducted a study on the propagation of solitary waves along the symmetry axis of idealised, symmetrical, converging water bodies. They discovered that Mach reflection has a substantial impact on the distribution of wave amplitudes in relatively wide channels and suggested a new predictive approach. However, it should be noted that the scenario of incident waves along the symmetrical axis of the water body is a special rather than a general case. Therefore, further study is needed to investigate the effect of converging water

body geometries on tsunami propagation in more general cases. This research aims to enhance our understanding of the physical mechanisms involved and support tsunami hazard assessment, with a focus on solitary wave interaction and wave amplitude distribution in converging water bodies.

NUMERICAL MODEL

The simulation of solitary wave propagation in converging channels with uniform depth at a small scale is conducted using SWASH v7.01 (Zijlema et al., 2011; Ruffini et al., 2019). SWASH can consider frequency dispersion accurately with a small number of layers (e.g. 2) by using a compact difference scheme and it was run in parallel. The water surface time series of 1st-order solitary waves, with water depth $h = 0.3$ m and normalised amplitude $a/h = 0.3$, are used as the input for SWASH on the finite straight wave generation boundary. A sponge layer with a length of 5 m is added at the end of the converging water bodies to absorb the waves (Figure 2). Different θ and $\Delta\psi$ were investigated, where θ is the water body side angle and $\Delta\psi$ is the angle of deviation between the incident wave direction and the axis of symmetry. However, due to space limitations, only a representative example of solitary wave propagation in the converging channel with $\theta = 11.25^\circ$ and $\Delta\psi = 3.75^\circ$ is presented herein.

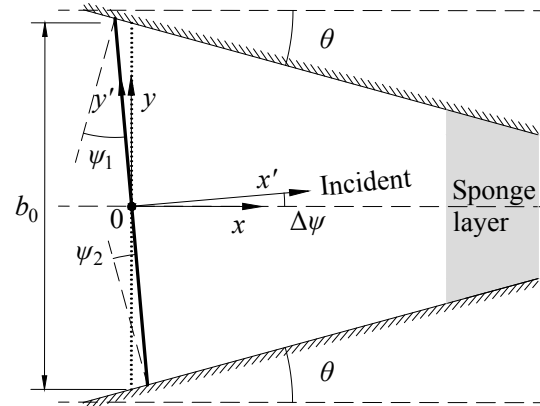


Figure 2. Schematic plan view of wave propagation in a converging channel. The origin of the (x, y) and (x', y') coordinate system is located at the midpoint of the basin mouth.

RESULTS

Assuming $\psi_1 \geq \psi_2$ and $\theta > \Delta\psi > 0^\circ$, the relationship between angles can be expressed as $\psi_1 = \theta + \Delta\psi$ and $\psi_2 = \theta - \Delta\psi$. In the representative case, the solitary wave interacts with the two sidewalls obliquely with $\psi_1 = 15^\circ$ and $\psi_2 = 7.5^\circ$. Figure 3 shows the contour of the normalised water surface elevation η/h snapshots for every 2 s. The propagation in the converging channel results in stem waves (Mach reflection) and transition slopes reaching the centre and superimposing. This effect intensifies with

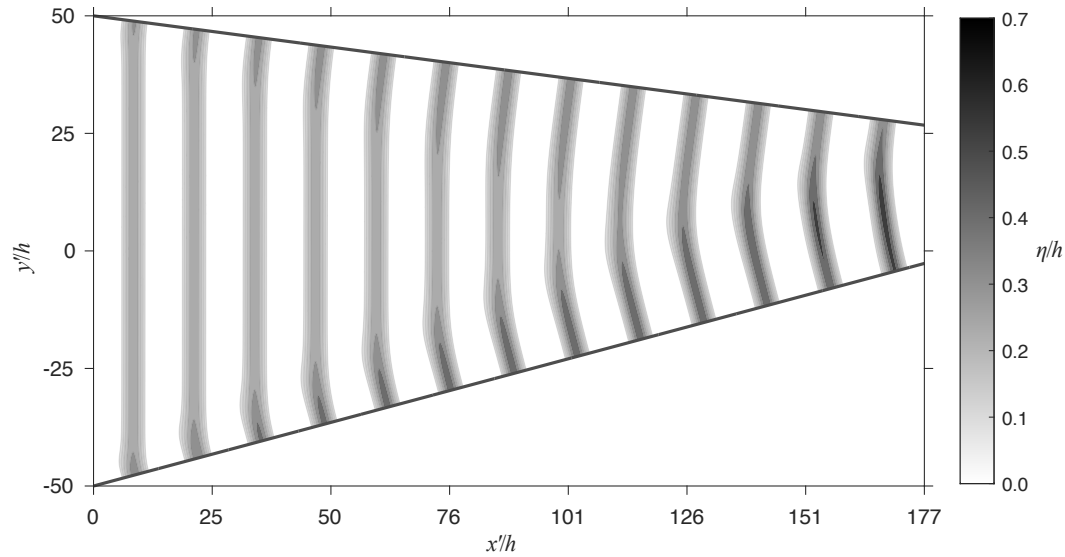


Figure 3. Plan view of η/h contour snapshots for every 2 s in the channel with $\theta = 11.25^\circ$ and $\Delta\psi = 3.75^\circ$.

increasing relative propagation distance x'/h and higher η/h at the centre can be observed at $x'/h = 151$. Note that due to the rough contour lines selected, the small reflected waves are not visible. However, the changing shape of the wavefront is clearly visible and the growth of l_s on the sidewall of ψ_1 is slower than that of ψ_2 . This aligns with the theory of Miles (1977): in Mach reflection, for a given solitary wave, the larger is ψ , the smaller becomes ψ_w .

As the wave amplitudes nearshore are most relevant in coastal engineering, Figure 4 shows a/h at the two sidewalls. At $x'/h = 100$, the stem waves on both sides have not yet interacted. Meanwhile, the increases of stem waves a/h almost vanish as they approach an asymptotic state of 0.49 (for ψ_1) and 0.38 (for ψ_2). The corresponding amplifications in relation to the initial value of 0.3 are 1.63 and 1.27, respectively, corresponding to a difference of 36%. With further propagation, the two stem waves meet each other, superpose and interact, resulting in a continued rapid increase in a/h .

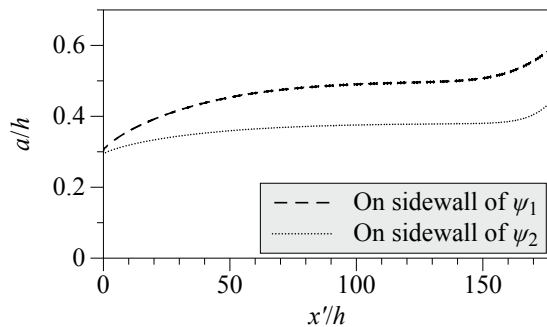


Figure 4. Relative wave amplitude a/h variation with x'/h along the two sidewalls.

CONCLUSIONS

This study investigated the effect of converging water bodies on tsunami propagation using the SWASH model. The propagation of solitary waves, as a proxy of tsunamis, in converging channels was simulated.

Different water body side angles θ and deviation angles of incidence from the axis of channel symmetry ψ were investigated. A representative case of $\Delta\psi = 3.75^\circ$ was presented for a solitary wave with an amplitude of 0.3 times the water depth propagating in a uniform-depth channel with $\theta = 11.25^\circ$. The wave produced different stem waves growth along the two sidewalls, resulting in increasing wave amplitudes by superposition and interaction. The results revealed that even small $\Delta\psi = 3.75^\circ$ could lead to significant uneven wave amplitude distribution, with a 36% difference in amplification coefficients between the two stem waves on the two sidewalls. These findings explain the effect of converging water bodies on wave propagation in general asymmetric situations and aimed to improve tsunami prediction and hazard assessment.

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