CFD Simulation of KCS Bow Wave Breaking in Calm Water and in Waves

Xinyi Li, Jianhua Wang, Decheng Wan*

Computational Marine Hydrodynamics Lab (CMHL), School of Ocean and Civil Engineering,
Shanghai Jiao Tong University, Shanghai, China
*Corresponding Author Email: dcwan@sjtu.edu.cn

HIGHLIGHTS

This study analyzes bow wave breaking in regular waves and compares the results with calm-water condition, assessing the influence of wave steepness on breaking severity and deck wetness. Furthermore, it investigates the evolution of wave profiles within an encounter period, analyzing the flow fields, wave height frequency characteristics, and the spatial distribution of kinetic energy.

1 INTRODUCTION

Wave breaking is highly unsteady and involves multiple temporal and spatial scales, as well as mechanisms such as turbulence, interface instability, and air entrainment[1]. Bow wave breaking occurs due to ship-water interaction and the wave breaking pattern depends on the hull curvature boundary conditions and ship motions. Spilling breaking is more common in full hull forms, while plunging breaking occurs more easily on fine-lined vessels [2]. The energy is rapidly dissipated through intense turbulent flows in bow wave breaking[3] , significantly increasing resistance and leading to higher fuel consumption and additional carbon emissions. Moreover, entrapped air can impair propulsion performance[4] and interfere with sonar operation.

Recently, bow wave breaking has gained research attention and was included as a key case in the 2025 Workshop on CFD in Ship Hydrodynamics. Multiple studies have been conducted in calm water to aid in understanding the mechanisms of bow wave breaking and provide data for CFD validation. Liu et al. [5]. analyzed fluctuation intensity and breaking dynamics for the KCS model via model tests and signal analysis. Xie et al.[6] numerically analyzed the relationship between the underwater velocity field and the wave profile in the bow wave breaking region of a surface ship. Wang et al.[7] studied the scale effects of structures on wave breaking. Mao et al.[8] conducted a quantitative and qualitative analysis of the breaking and air entrainment process. Li et al.[9] examined the spatiotemporal characteristics and key time scales for the KCS model. Wilson et al.[10] investigated the influence of bow wave breaking on the distribution of turbulent kinetic energy and vortex structures. Shao et al.[11] conducted extremely high-fidelity simulations of wave breaking for a simplified bow structure. Li et al.[12] performed a frequency-dependent detailed study on wave breaking for a simplified bow structure.

Despite these insights, ships predominantly operate in realistic wave environments, where steep and hazardous sea conditions can exacerbate bow wave breaking and its associated energy losses. To address this gap, the present study specifically investigates bow wave breaking under wave conditions. High-fidelity numerical simulations are performed using refined grids, advanced turbulence models, and overset grid techniques to investigate the flow characteristics, wave evolution, and turbulent kinetic energy.

2 NUMERICAL METHODOLOGY

2.1 Geometry and Numerical Conditions

The ship model used in this study is a 1:37.89 scale model of the KCS hull form, with a length between perpendiculars L_{PP} of 6.0702 m. Its specific geometry is shown in Figure 1. In calm water, the model is fixed at a trim of 1° by the bow and moves at a speed corresponding to Fr = 0.35. In waves, the model is free to move in heave and pitch.

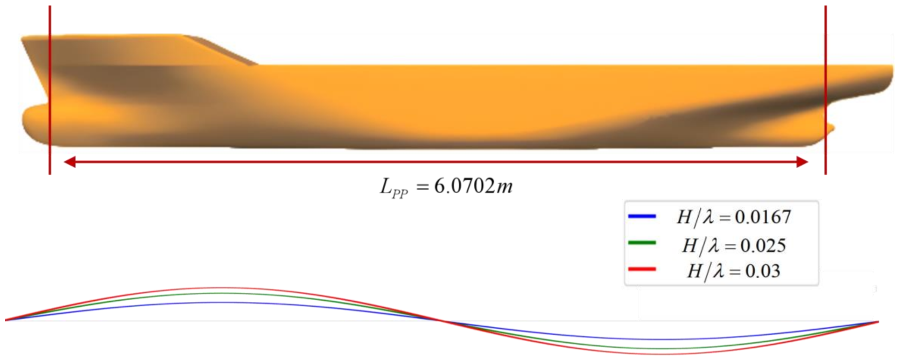


Figure 1: Geometry of KCS model and wave conditions

The wavelength is set to $\lambda = 1.15\ L_{PP}$, with wave steepness H/λ of 0.0167, 0.025, and 0.03. In full-scale conditions, these H/λ correspond to Sea State 6 and Sea State 7, which are considered high-risk sea states. The forward speeds are set to Fr = 0.26 and Fr = 0.35.

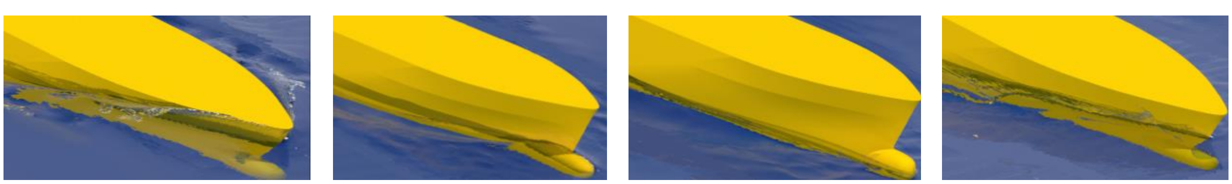
2.2 High-fidelity Numerical Simulation Method

To achieve high-fidelity simulation of bow wave breaking under wave conditions, this study employs a high-precision Delayed Detached Eddy Simulation (DDES) turbulence model. The DDES approach utilizes Large Eddy Simulation (LES) away from the wall to capture the detailed free-surface features in the breaking region. Furthermore, to accurately simulate the ship model's large-amplitude motions under high wave steepness, the overset grid technique is adopted. This effectively captures the wave fluctuations induced by the ship's motion.

3 PRELIMINARY RESULTS

3.1 Wave Profiles

As shown in fig. 2 to fig. 4, compared to calm water, the wave profile in waves exhibits enhanced periodic coherence and a rearward shift of the plunging location. Under high wave steepness, breaking intensifies and becomes more energetic, resulting in green water on deck.



(a) $T = T_e / 4$ (b) $T = T_e / 2$ (c) $T = 3T_e / 4$ (d) $T = T_e$

Figure 2: Wave profiles when $H/\lambda = 0.0167$

(a) $T = T_e / 4$ (b) $T = T_e / 2$ (c) $T = 3T_e / 4$ (d) $T = T_e$

Figure 3: Wave profiles when $H/\lambda = 0.03$

Figure 4: Wave profiles in calm water

3.2 Frequency Characteristics of Wave Height

Given the periodic nature of wave breaking in calm water, the dominant frequency energy ratio σ_h was plotted and compared against the RMS of wave height fluctuations to characterize the principal frequency characteristics of different breaking phenomena in fig. 5. Considering the periodic nature of wave breaking in waves as well, the spectral characteristics and key energy frequency bands of KCS bow wave breaking in waves will be further examined in the full study.

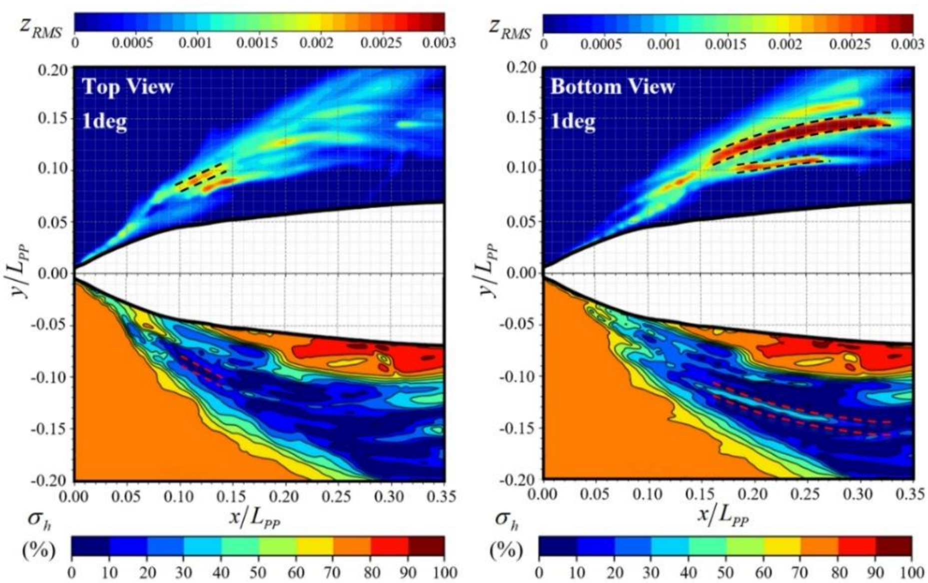


Figure 5: Frequency feature of KCS in calm water

3.3 Spatial Distribution of Kinetic Energy

Fig. 6 presents the spatial distribution of normalized kinetic energy E_k^* along the x and y axes within the bow wave breaking region under the calm water condition. Building on these baseline results, a comparative analysis of wave conditions will be performed in the full work.

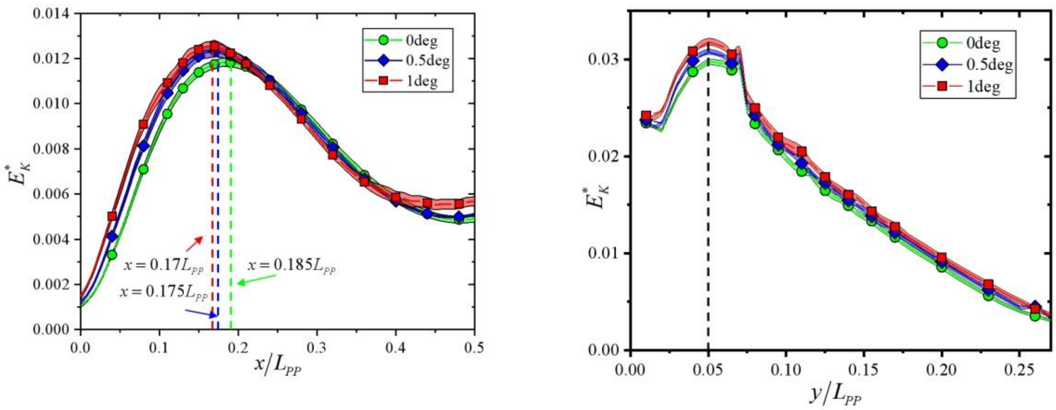


Figure 6: Spatial distribution of E_k^* for the KCS in calm water

4 PRELIMINARY CONCLUSIONS AND FULL WORK

The present study focuses on comparing wave evolution in waves versus calm water. Wave conditions and steepness are found to significantly influence the form and periodicity of bow wave breaking. Furthermore, the differences in breaking characteristics between calm water and wave conditions will be analyzed in detail in the full work, particularly regarding the associated flow fields, frequency spectra, and kinetic energy distribution.

REFERENCES

[1] Wang, Z., Yang, J., Stern, F., 2010. *Numerical simulations of wave breakings around a wedge-shaped bow.* The 28th Symposium on Naval Hydrodynamics, Pasadena, California.

[2] Deike L, Popinet S, Melville W K., 2015. *Capillary effects on wave breaking*. Journal of Fluid Mechanics, 769, 541-569.

[3] Iafrati A. 2011. *Energy dissipation mechanisms in wave breaking processes: spilling and highly aerated plunging breaking events*. Journal of Geophysical Research: Oceans, 116(C7).

[4] Kawabuchi M, Kawakita C, Mizokami S, et al., 2011. *CFD predictions of bubbly flow around an energy-saving hip with Mitsubishi air lubrication system*. Mitsubishi Heavy Industries Technical Review, 48(1), 53-57.

[5] Liu W., Wang W., Qiu G. et al., 2022. *KCS Unsteady bow wave breaking experiments for physics and CFD validation*. The 34th Symposium on Naval Hydrodynamics, Washington DC, USA.

[6] Xie L., Wan D., 2020. *Refined numerical simulation of the bow wave breaking process for the KCS ship model.* The 31st National Symposium on Hydrodynamics, Fujian,China.

[7] Wang J., Wang W., Wan D., 2023. *Scale effects on bow wave breaking of KCS ship model: Insights from DDES investigations*. Journal of Hydrodynamics, 35(4), 668-678.

[8] Mao T, Bao F, Wang J, et al., 2024. *Numerical study of air cavity characteristics of bow wave breaking of KCS ship under different speeds*. Journal of Hydrodynamics, 36(4), 678-692.

[9] Li X, Bao F, Wang J, et al., 2024. *Spectral and statistical analysis of bow wave breaking characteristics of KCS ship*. Journal of Hydrodynamics, 36(4), 593-608.

[10] Wilson R V, Carrica P M, Stern F., 2007. *Simulation of ship breaking bow waves and induced vortices and scars*. International journal for numerical methods in fluids, 54(4), 419-451.

[11] Shao Y., Song B., Wang J., et al., 2025. *Wave breaking characteristics around a wedge-shaped bow: High-fidelity simulation of water–air–bubble mixed flow*. Physics of Fluids, 37, 072124.

[12] Li X., Song B., Wang J., et al., 2025. *Multidimensional numerical analysis of wedge-shaped bow wave breaking: Statistical signatures, critical frequencies, and energy distribution*. Ocean Engineering, 339, 122118.