Journal of Zhejiang University-SCIENCE A

Numerical investigation of the flow pattern around a vertical cylinder under wave action

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Cite this as: Ben HE, Junkang WENG, Yuan LIN, Yifan GAO, Maoxing WEI, Fang HE, 2026. Numerical investigation of the flow pattern around a vertical cylinder under wave action. *Journal of Zhejiang University-SCIENCE A*, 27(2):142-154. https://doi.org/10.1631/jzus.A2500436

Objectives

■**In this study, we numerically investigate the formation of vortices around a vertical cylinder under wave action, emphasizing the role of the flow field in potential bed erosion.**

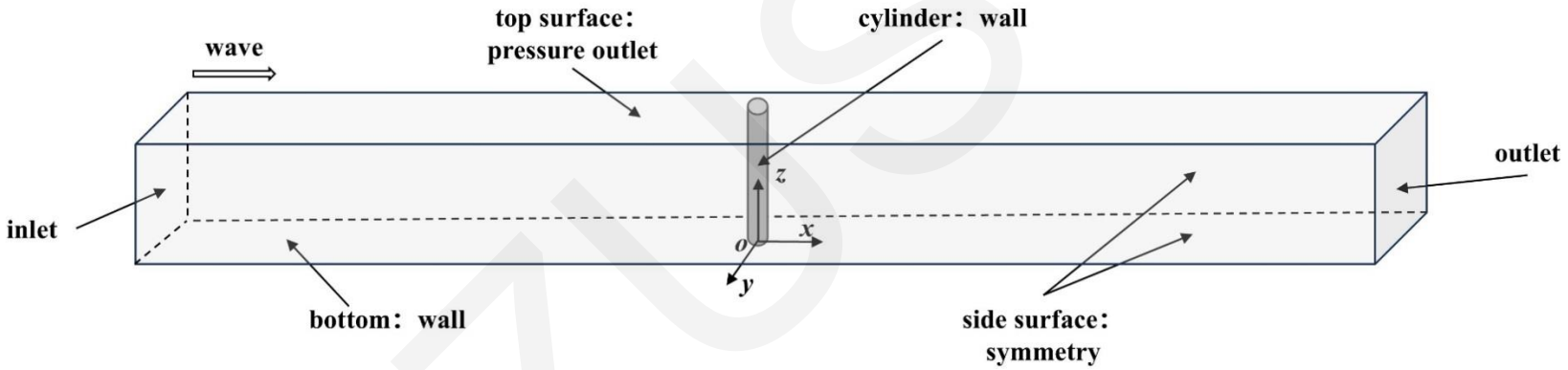


Fig. 1 Schematic diagram for the simulation domain showing the boundary conditions

In all tested cases, the water depth (h=0.40 m) and the diameter of the cylinder (D=0.03 m) were held constant. By varying the wave height (H) and period (T), a range of KC numbers was achieved.

Streamlines and velocity distribution

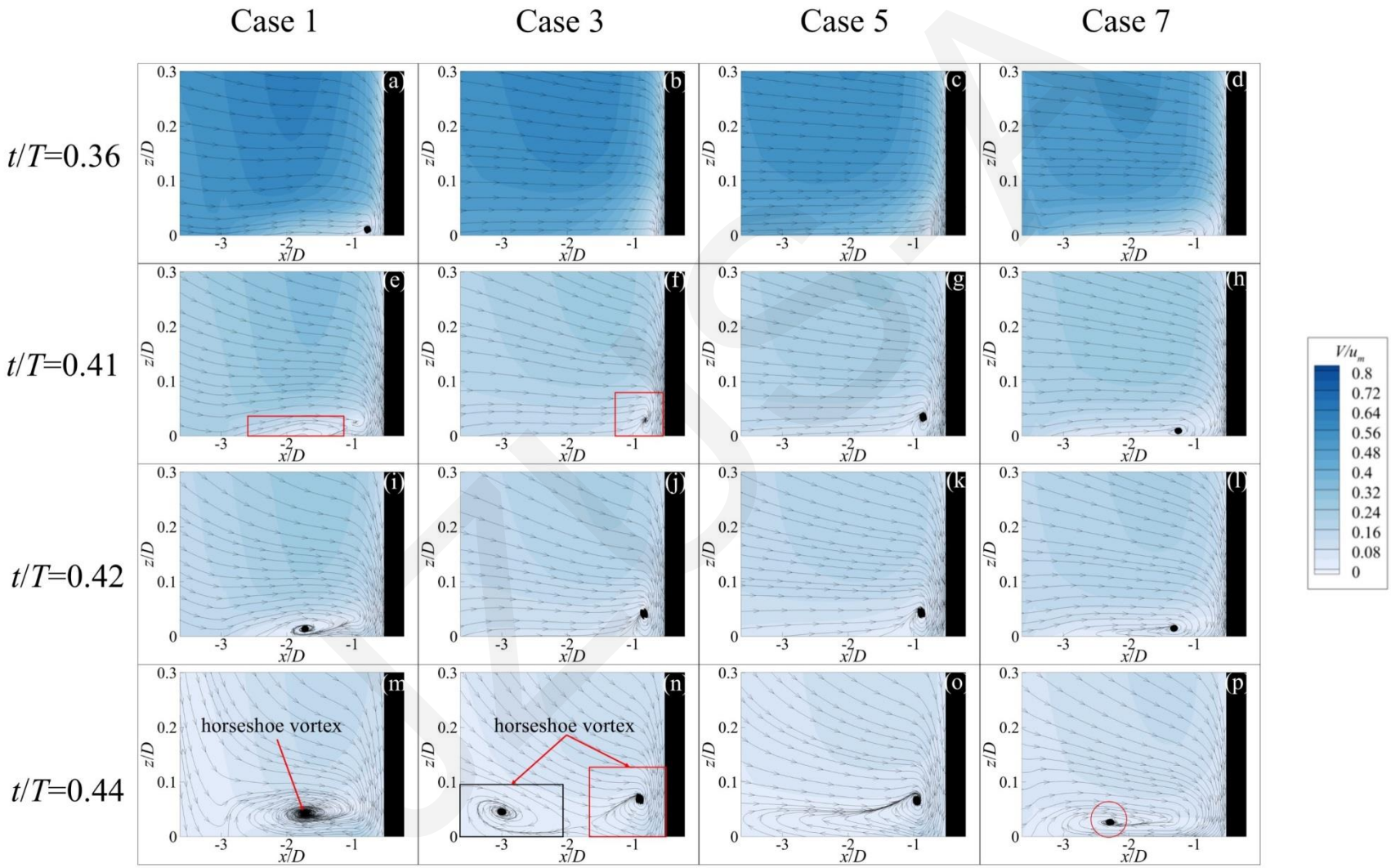


Fig. 3 Streamlines and velocity distributions in front of the cylinder

Analyses of vortex strength

$$\Gamma = \oint \vec{V} dC = \iint \omega \, \mathrm{d}S$$

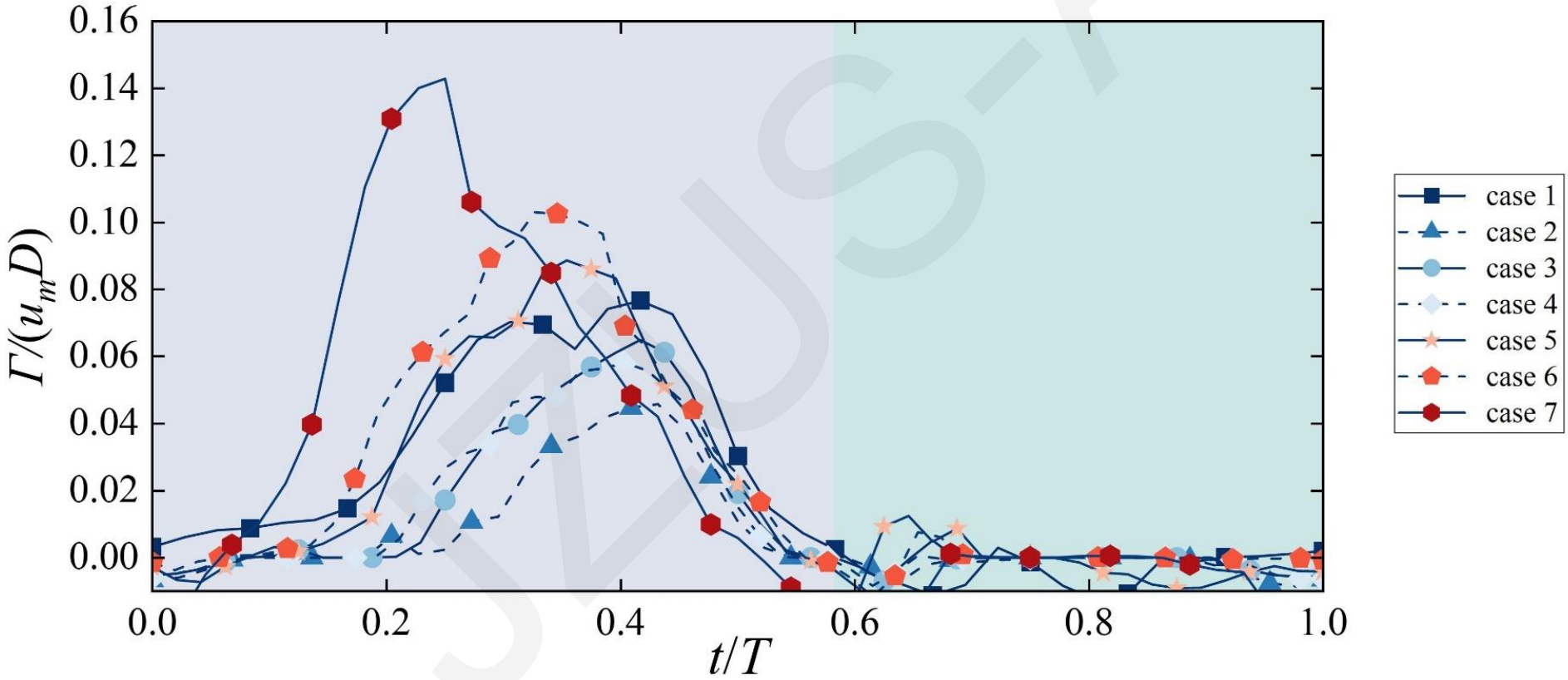
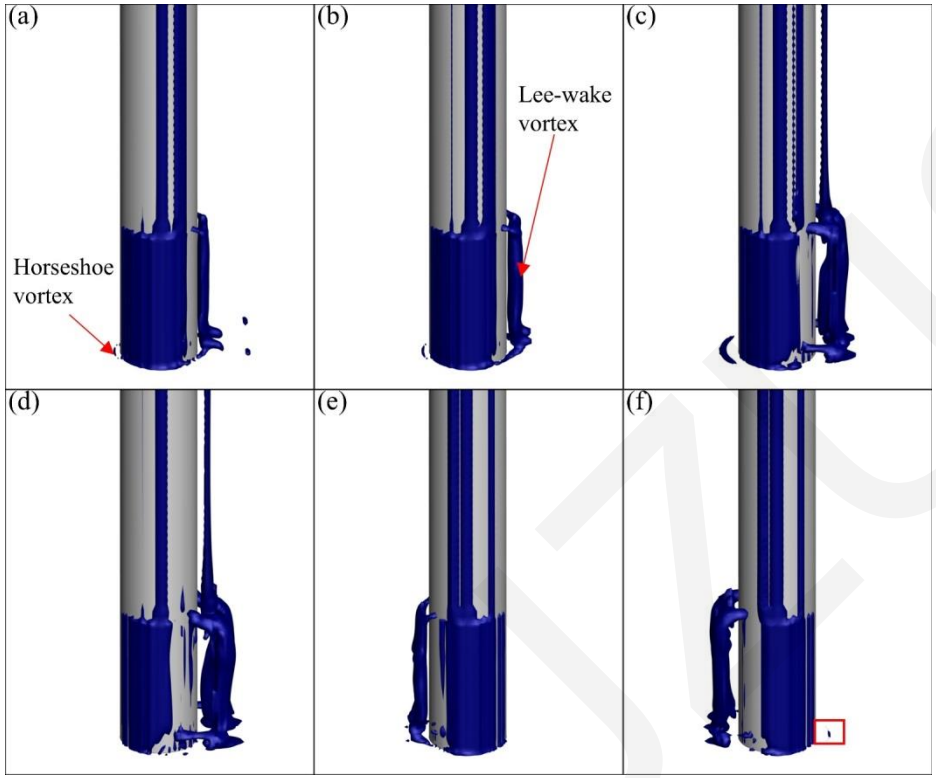


Fig. 4 Vortex strength in front of the cylinder for each case

Analyses of vortex strength

$$Q = \frac{1}{2}\left(\|\Omega\|^2 - \|S\|^2\right)$$



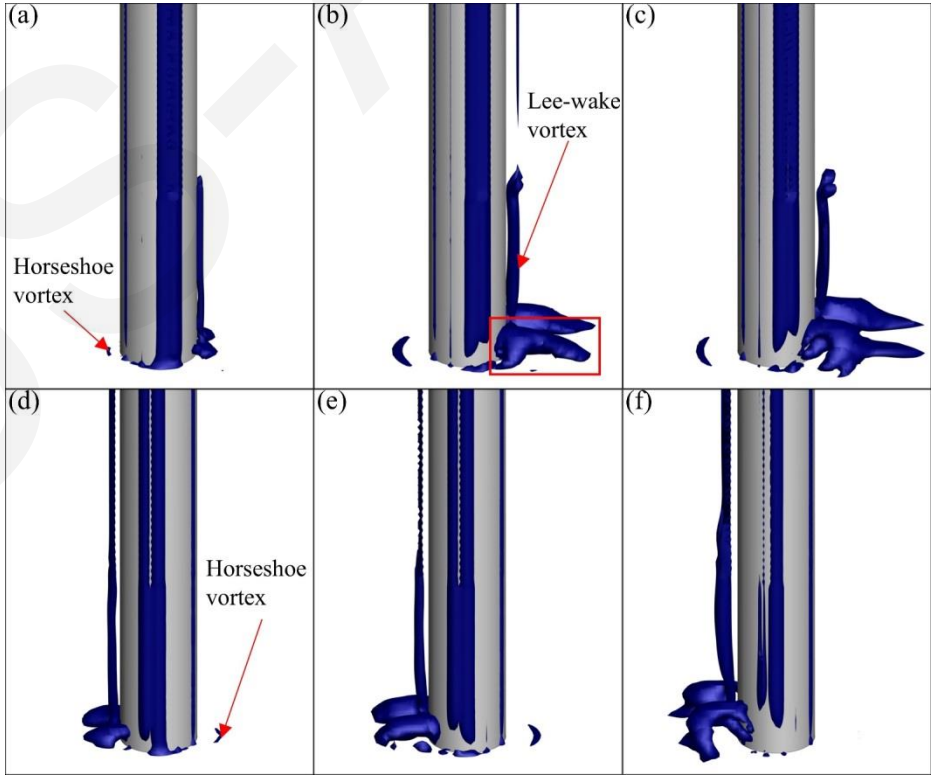


Fig. 5 Q criterion contour around the cylinder at different phases in Case 1 (a) *t/T* = 0.24; (b) *t/T* = 0.26; (c) *t/T* = 0.39; (d) *t/T* = 0.45; (e) *t/T* = 0.74; (f) *t/T* = 0.88

Fig. 6 Q criterion contour around the cylinder at different phases in Case 7 (a) t/T = 0.15; (b) t/T = 0.30; (c) t/T = 0.38; (d) t/T = 0.74; (e) t/T = 0.84; (f) t/T = 0.95

Analyses of bed shear stress

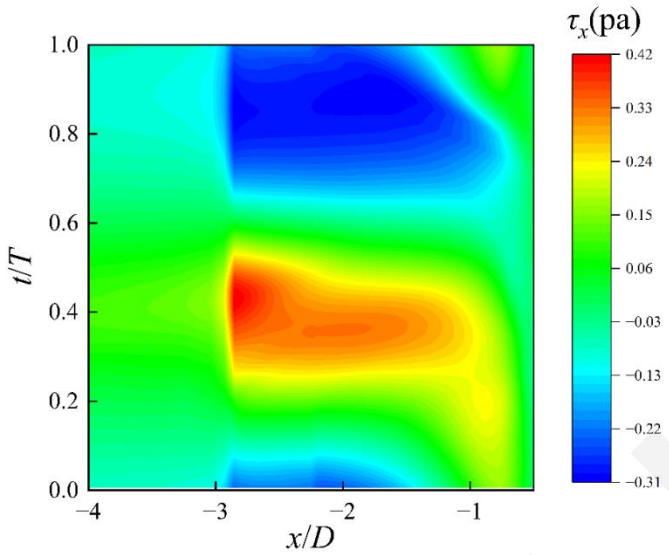


Fig. 11 Instantaneous bed shear stress contour in front of the cylinder in Case 1

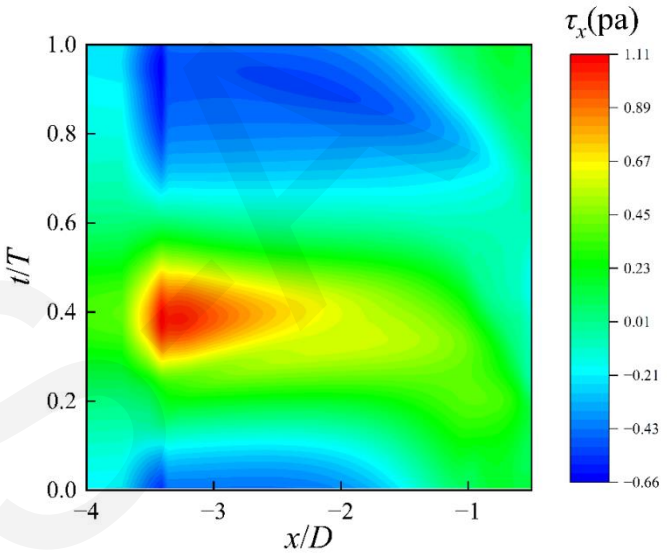


Fig. 12 Instantaneous bed shear stress contour in front of the cylinder in Case 7

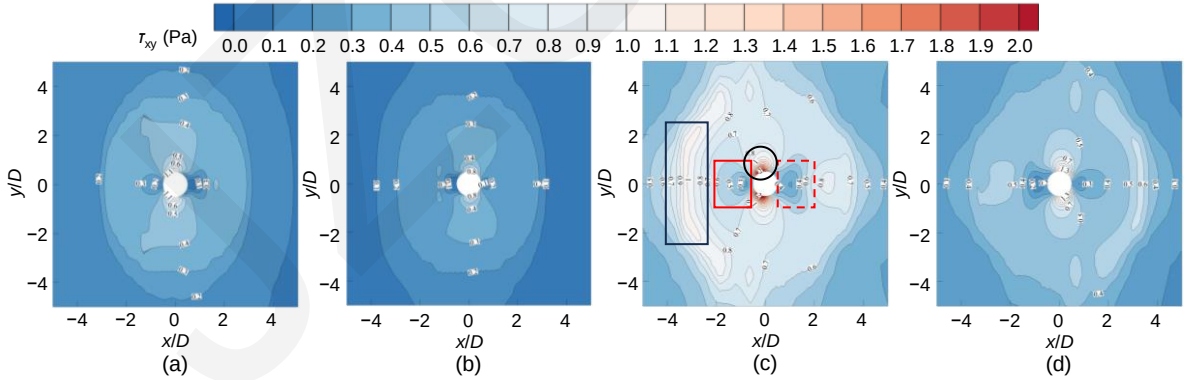


Fig. 13 Instantaneous bed shear stress contour around the cylinder: (a) Case 1 at *t/T*=0.40; (b) Case 1 at *t/T*=0.84; (c) Case 7 at *t/T*=0.40; (d) Case 7 at *t/T*=0.84

Conclusions

- At low KC numbers, the flow predominantly manifested as a single vortex structure. In contrast, high KC number cases showed coexistence of multiple vortices with significantly enhanced strength and a wider spatial extent.
- Analysis of the dynamic pressure revealed a persistent negative pressure gradient along the cyl-inder surface, which promoted flow separation and propagation of horseshoe vortices. Notably, within the angular range of $35^\circ < \varphi < 180^\circ$, a temporally evolving positive pressure gradient was identified, which intensifies separation between the boundary layers and fosters the formation of lee-wake vortices, ultimately influencing scour development patterns.
- The 3D vortex structures identified by the Q criterion analysis revealed distinct evolutionary processes. At low KC numbers, the vortices demon-strated stable evolutionary patterns, while in high KC number cases, accelerated formation of the horseshoe vortex and prolonged vortex lifetimes were observed.
- The distribution of bed shear stress was closely related to the activity of horseshoe vortices and lee-wake vortices. When upstream horseshoe vortices were active, the bed shear stress generated positive peaks near the cylinder. During the development of lee-wake vortices, the bed shear stress exhibited negative extremes, which may lead to the deposition and redistribution of sediment during scouring.