

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

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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.

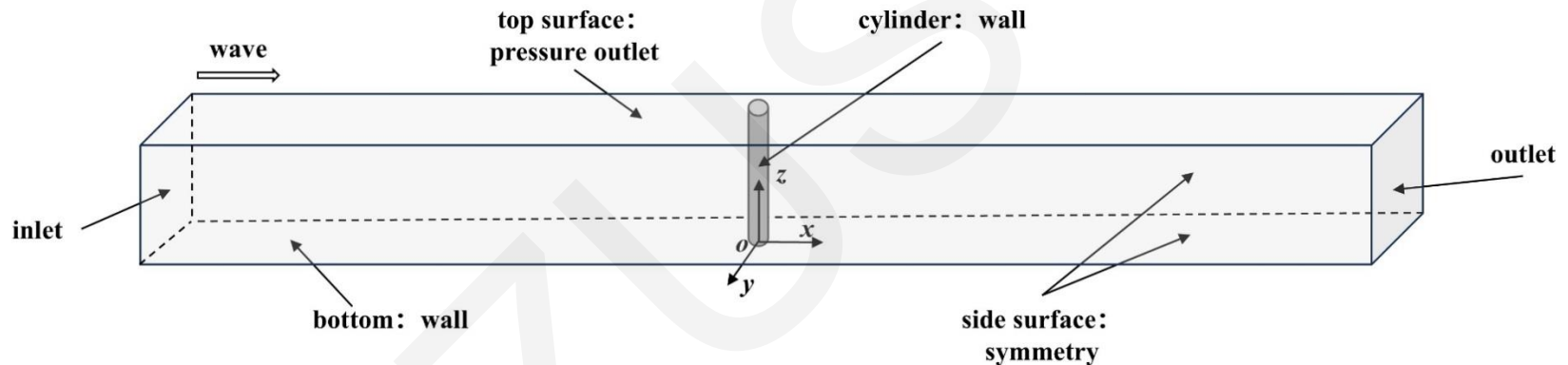


Fig. 1 Schematic diagram for the simulation domain showing the boundary conditions

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

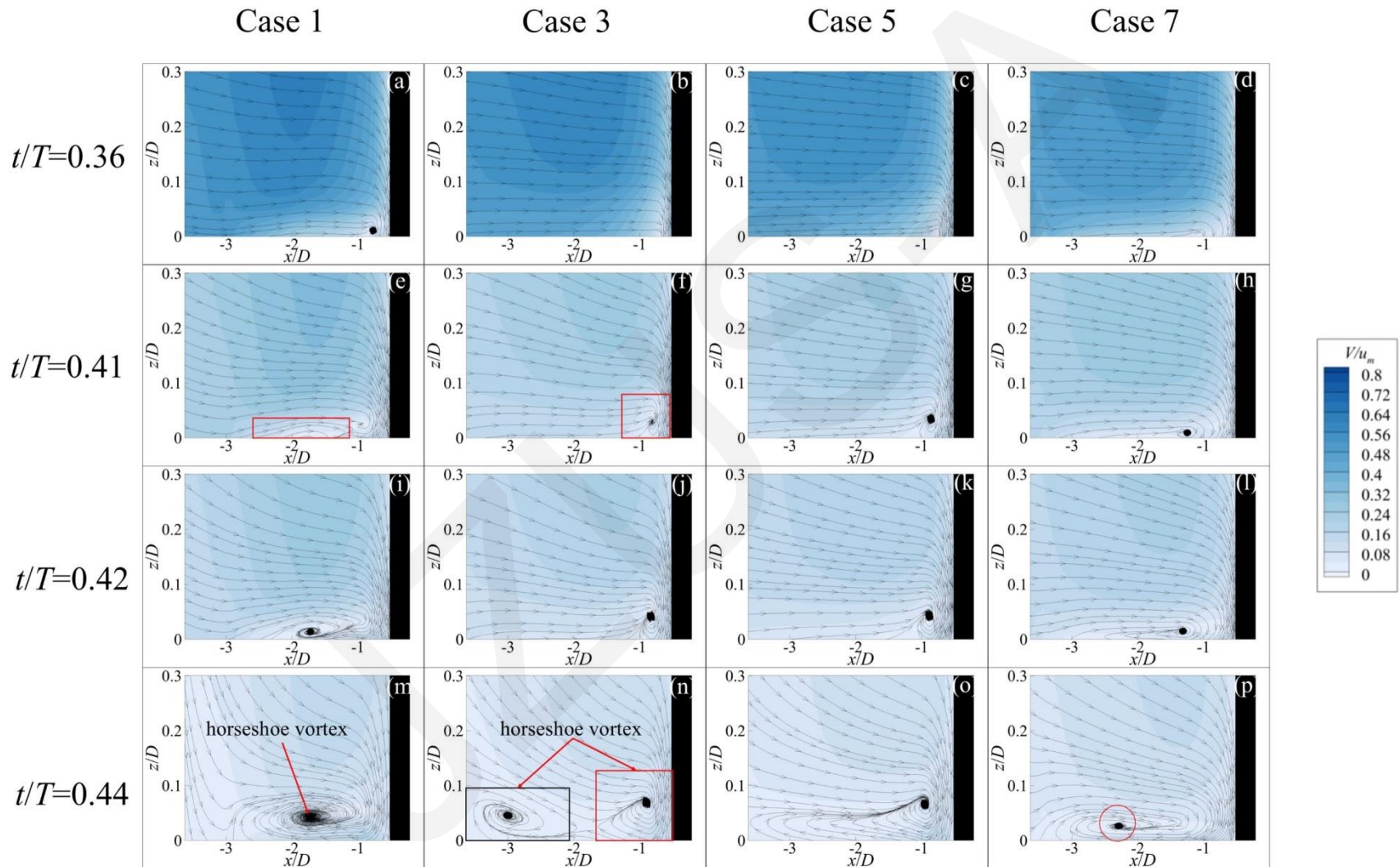


Fig. 3 Streamlines and velocity distributions in front of the cylinder

Analyses of vortex strength

$$\Gamma = \oint \vec{V} dC = \iint \omega dS$$

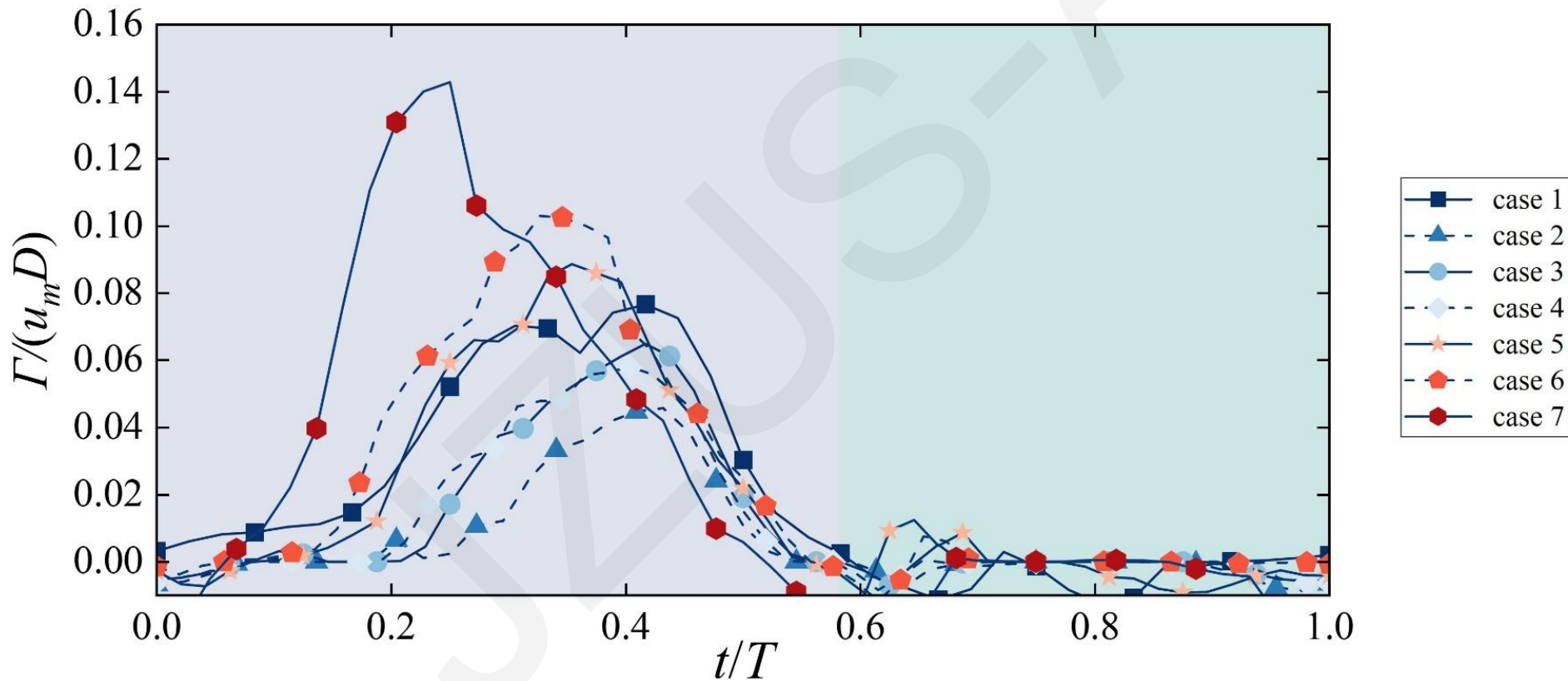


Fig. 4 Vortex strength in front of the cylinder for each case

Analyses of vortex strength

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

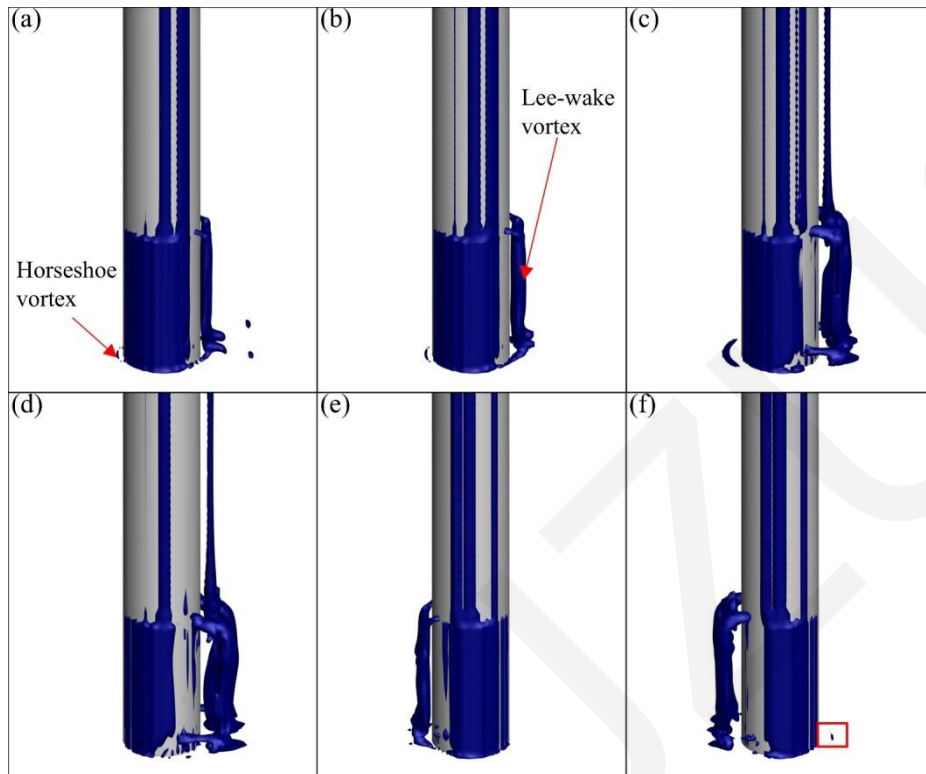


Fig. 5 Q criterion contour around the cylinder at different phases in Case 1 (a) $t/T = 0.24$; (b) $t/T = 0.26$; (c) $t/T = 0.39$; (d) $t/T = 0.45$; (e) $t/T = 0.74$; (f) $t/T = 0.88$

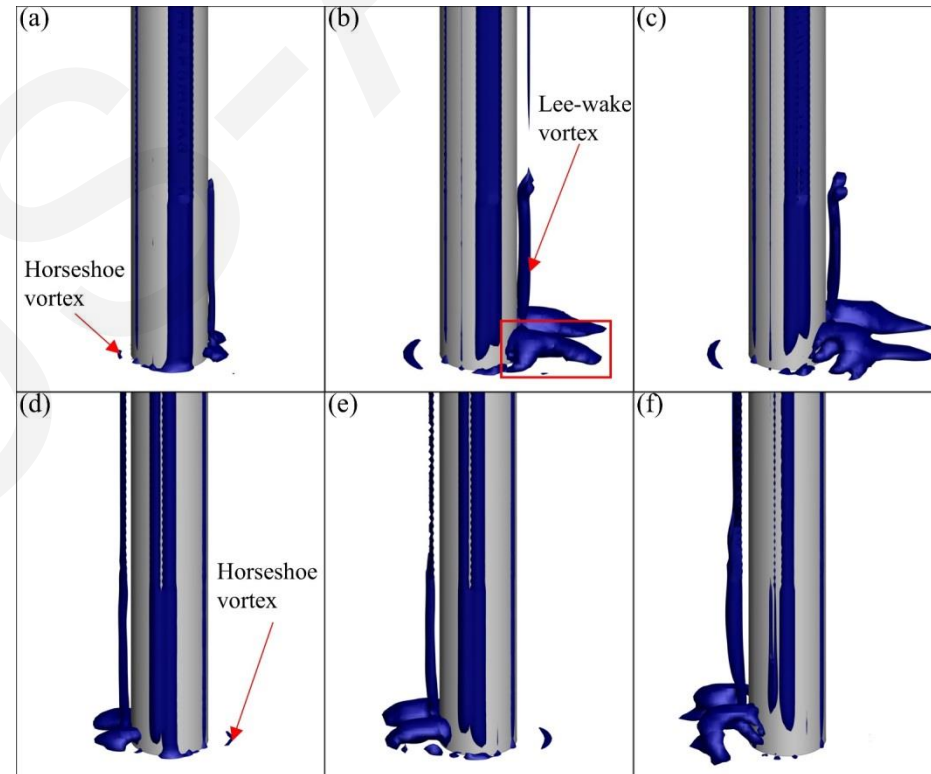


Fig. 6 Q criterion contour around the cylinder at different phases in Case 7 (a) $t/T = 0.15$; (b) $t/T = 0.30$; (c) $t/T = 0.38$; (d) $t/T = 0.74$; (e) $t/T = 0.84$; (f) $t/T = 0.95$

Analyses of bed shear stress

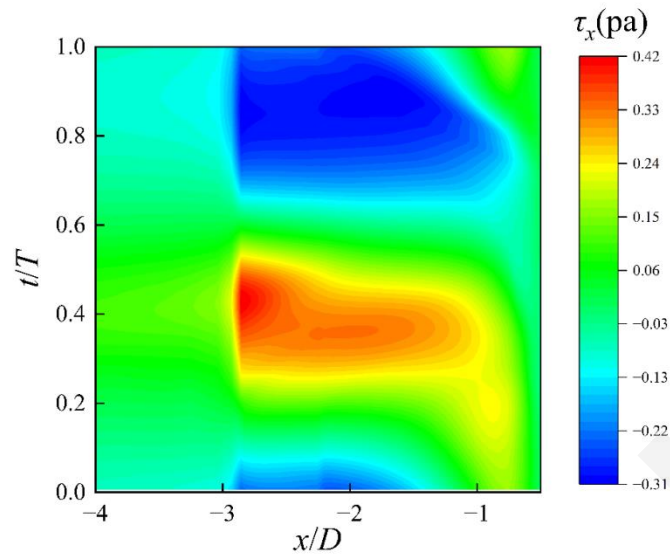


Fig. 11 Instantaneous bed shear stress contour in front of the cylinder in Case 1

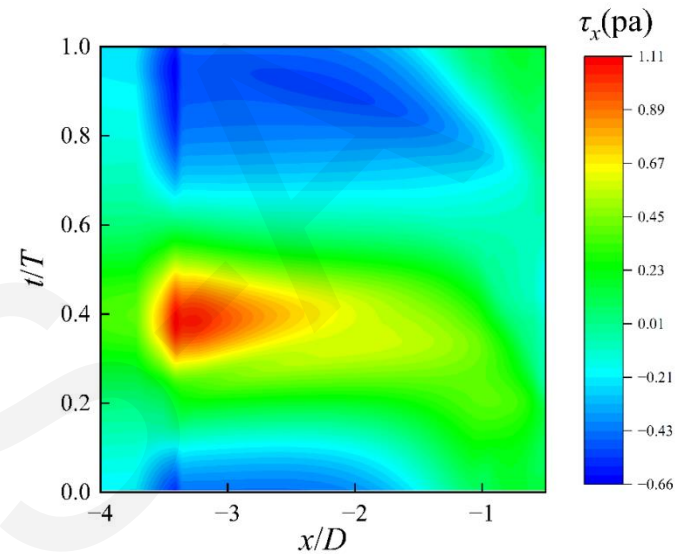


Fig. 12 Instantaneous bed shear stress contour in front of the cylinder in Case 7

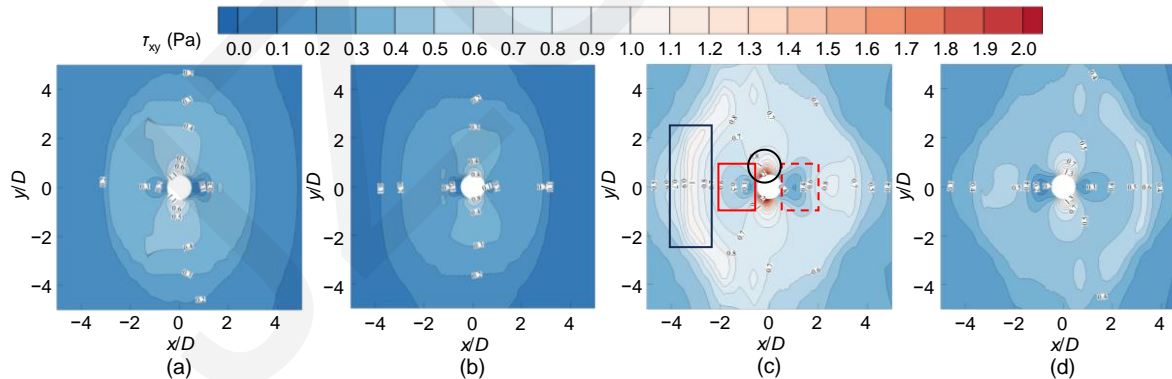


Fig. 13 Instantaneous bed shear stress contour around the cylinder: (a) Case 1 at $t/T=0.40$; (b) Case 1 at $t/T=0.84$; (c) Case 7 at $t/T=0.40$; (d) Case 7 at $t/T=0.84$

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 cylinder 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 demonstrated 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.