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Insights of abrasive water jet slotting mechanisms in hard rock using CFD-DEM simulation



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ABSTRACT

Abrasive water jet (AWJ) slotting technology shows great potential for stimulating oil and gas reservoirs, particularly in hard rock formations. Understanding the transport mechanisms of water and abrasives within the slot is crucial for optimizing performance. In this study, a fluid-structure interaction model incorporating slot geometry, water flow, and abrasive particles was developed using a coupled computational fluid dynamics-discrete element method (CFD-DEM). The effects of nozzle position, slot geometry, and jet parameters were systematically examined. Analysis of water turbulence, abrasive velocity distribution, and wall impact forces revealed the fundamental mechanisms of AWJ slotting in hard rock. Slot length determines the slot's cross-sectional area and the turbulence intensity, while jet distance and slot depth govern the turbulence pathway. Water turbulence controls jet kinetic energy dissipation, which further affects abrasive acceleration and the resulting impact force on slot walls. Abrasive transport follows a distinct pattern: decelerating during inflow, turning at the slot bottom, and accelerating along the sidewalls toward the annulus via backflow. Notably, impact forces are significantly higher on the slot bottom than on the sidewalls, driven by both abrasive velocity and impact angle. AWJ slotting offers more efficient rock breaking and deeper perforation than conventional AWJ perforation by moving the nozzle to enlarge the slot cross-section, reduce turbulence, and preserve jet kinetic energy for rock removal. A nozzle moving range of approximately 10 times the nozzle diameter is recommended. These findings offer key insights into AWJ slotting in hard rock, highlighting the coupled dynamics of water, abrasives, and slot geometry, and providing guidance for parameter optimization in field applications.

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1. Introduction

Abrasive water jet (AWJ) rock breaking technology is widely employed in underground engineering (Chernyshov et al., 2015; Liu et al., 2019, 2023). Among various nozzle designs, the conical straight nozzle is the most commonly used due to its simple fabrication, effective acceleration of the water-abrasive mixture, and concentrated jet energy. It is typically applied in two configurations: fixed nozzles for rock perforation or mobile nozzles for

rock cutting (Natarajan et al., 2020). With the growing demand for efficient volumetric fracturing in horizontal wells within tight hard rock reservoirs, a novel technique utilizing a reciprocating torsional jet gun for AWJ slotting has been developed (Xu et al., 2025a). This technology involves the reciprocating movement of the nozzle within a defined range to create slot-like perforations in the rock. Studies have demonstrated that AWJ slotting outperforms traditional AWJ perforation in terms of the rock breaking efficiency and the penetration depth. Additionally, the generated slots help reduce fracture initiation pressure and promote controlled fracture direction. However, current understanding of AWJ slotting is primarily based on experimental observations, and there is a lack of theoretical analysis to support its application and optimization in the field.

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The macroscopic morphology of AWJ-induced slots results from the cumulative meso-scale rock damage caused by prolonged jet impact. Xu et al. (2025b) conducted AWJ rock slotting experiments and reported that at a jet velocity of 250 m/s for 90 s, the resulting slot reached a depth of approximately 150 mm and exhibited a sword-like shape. At the mineral scale, AWJ-induced damage is characterized by the progressive formation of micro-cracks within mineral clusters under repeated jet impacts, ultimately leading to particle spalling (Li et al., 2024). For hard rocks such as dense sandstone, shale, and granite, high-frequency abrasive erosion is the dominant mechanism of rock breakage (Li et al., 2022; Qu et al., 2022b). Li et al. (2023) developed a numerical model of abrasive water jet breaking in granite and found that jet diffusion at the bottom of the erosion pit played a key role in rock breakage. Cai et al. (2019) used CT scanning to analyze the perforation morphology and observed backflow characteristics, showing that the internal flow field evolves with changes in perforation geometry and significantly influences the final outcome. Peng et al. (2025) quantitatively analyzed AWJ perforation evolution and identified three coupled flow effects: inflow deepens the perforation, backflow widens it, and turbulence dissipates jet energy. These findings underscore that AWJ rock breaking is jointly controlled by jet-induced rock damage and the internal flow dynamics within the erosion pit. While the mesoscopic damage mechanism remains consistent across different nozzle shapes and movement patterns, variations in pit geometry alter the internal flow behavior and ultimately affect rock breaking efficiency. Consequently, a detailed investigation into the in-slot dynamics of water and abrasive particles is essential for a deeper understanding of AWJ slotting mechanisms.

Advancements in computational fluid dynamics (CFD) have provided a solid foundation for analyzing the complex kinematics of high-velocity jets (Liu et al., 2025a; Wei et al., 2025). Early studies on abrasive water jet flow in perforations typically assumed a uniform distribution of abrasive particles, and thus simulated only the water phase to evaluate the erosion effect (Liu, 2007; Surjaatmadja and Gijtenbeek, 2011). As understanding of the non-uniform distribution of abrasives in the jet improved, and attention shifted toward abrasive acceleration efficiency within nozzles, the discrete phase model (DPM) was introduced to simulate particle behavior (Qiang et al., 2018). Sheng et al. (2020) developed a CFD-DPM model to investigate erosion patterns within jetting tools, revealing detailed erosion distributions inside nozzles. The DPM is suitable for dilute particle flows with abrasive volume concentrations below 10%, as it neglects inter-particle interactions. However, while the average abrasive concentration in AWJ systems remains under this threshold, localized concentrations can exceed 10%, particularly near the nozzle due to jet acceleration or within perforation zones as a result of particle deceleration and accumulation. The discrete element method (DEM), which models each particle as an individual body and considers interactions such as contact, collision, and friction, is more appropriate for high-concentration scenarios where particle interactions significantly affect flow behavior (Qu et al., 2022a). In industrial applications, CFD-DEM models have been employed to simulate water-particle mixtures in machinery at flow velocities below 120 m/s (Liang et al., 2024; Scott et al., 2022). For high-velocity AWJ systems, CFD-DEM modeling has been applied to study abrasive acceleration within nozzles, free jet flow characteristics, and jet impact on flat surfaces (Li et al., 2014; Metzger and Mehring, 2024; Tang et al., 2024). However, research on the flow behavior of high-speed AWJ in specific hole geometries using the

CFD-DEM approach remains limited. Therefore, it is essential to develop a high-speed AWJ slotting model based on CFD-DEM, and investigating the internal flow dynamics and abrasive-wall interaction within the slot can provide critical insights into the fundamental mechanisms of AWJ slotting in hard rock.

In this study, a coupled CFD-DEM fluid-structure interaction model was developed that incorporates water flow, abrasive particles, and critically considers realistic slot geometry. The effects of nozzle position, slot length, slot depth, jet velocity, and jet distance were systematically analyzed. By examining water turbulence, abrasive velocity distributions, and wall impact forces, the fundamental mechanisms governing AWJ slotting in hard rock were revealed.

2. Numerical model

2.1. CFD-DEM coupling algorithm

2.1.1. Continuous phase

The water-abrasive flow within the slot was simulated using a coupled computational fluid dynamics-discrete element method (CFD-DEM) (Li et al., 2014). The continuous fluid phase was solved using ANSYS Fluent®, while the discrete particle phase was handled in Altair EDEM®. A user-defined function (UDF) was employed to establish the coupling interface for the two platforms (Krause et al., 2017). At each time step, the CFD module first solved and converged the flow field, which was then transferred to the DEM module. In the DEM module, a drag model was used to calculate the fluid drag forces acting on the particles. External forces on each particle were computed to update their positions and velocities. These dynamic parameters were then passed back to the CFD module as momentum source terms. This iterative process enabled two-way coupling between the fluid and particle phases.

Water, modeled as the continuous phase, was simulated using the CFD module. The continuity and momentum conservation equations for the continuous phase are expressed as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{g} + \mathbf{F}_{\text{DEM}} \quad (2)$$

where, ρ is the fluid density, kg/m³; t is time, s; $\mathbf{u}$ is the fluid velocity vector, m/s; p is the pressure, Pa; $\boldsymbol{\tau}$ is the viscous stress tensor, Pa; $\mathbf{g}$ is the gravitational acceleration vector, m/s²; $\mathbf{F}_{\text{DEM}}$ is the interaction force per unit volume exerted by the discrete phase on the fluid, calculated via CFD-DEM coupling, N/m³.

The realizable k - ε turbulence model was adopted to simulate dispersed turbulence, with the scalable wall function (SWF) applied. Pressure-velocity coupling was handled using the semi-implicit method for pressure-linked equations consistent algorithm (SIMPLEC) (Jasak, 1996).

2.1.2. Discrete phase

Abrasives, modeled as the discrete phase, were simulated using the DEM module. The soft-sphere approach was employed to model both particle-particle and particle-wall interactions. The Hertz-Mindlin (no-slip) contact model was adopted, in which the normal contact force was computed based on Hertzian contact theory, while the tangential force followed the Mindlin-

Deresiewicz formulation (Hertz, 1881; Mindlin and Deresiewicz, 1953). Both force components included damping terms to account for energy dissipation (Tsuji et al., 1993). Tangential friction was governed by Coulomb's law, and rolling friction was modeled using a constant-torque approach independent of contact conditions (Cundall and Strack, 1979; Sakaguchi et al., 1993). According to Newton's second law, the motion of each abrasive particle is described by the following equation:

$$m_a \frac{dv_a}{dt} = m_a g + \sum F_c + F_d + F_{sf} + F_{mf} + F_m + F_p + F_b \quad (3)$$

where, m_a is the mass of the abrasive particle, kg; v_a is the velocity vector of the abrasive particle, m/s; F_c denotes the contact force, including abrasive-abrasive and abrasive-wall interactions, N; F_d is the fluid drag force, N; F_{sf} is the Saffman lift force due to shear, N; F_{mf} is the rotational lift force (Magnus effect), N; F_m is the virtual mass force, N; F_p is the pressure gradient force, N; F_b is the Basset history force. Detailed explanations of these variables were provided by Qu et al. (2022b).

Fig. 1 illustrates the fundamental mechanical interactions involved in fluid-solid coupling between water, abrasives, and the wall. When the velocity gradient in the water is low, the flow remains laminar, characterized by orderly motion and minimal kinetic energy dissipation. As the velocity gradient increases, the flow transitions to turbulence, marked by chaotic motion and significantly higher energy dissipation. Turbulence intensity can be quantitatively evaluated using the turbulent kinetic energy k , with larger values indicating stronger turbulence. It is defined as:

$$k = \frac{1}{2} (\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \quad (4)$$

where, k is the turbulent kinetic energy, representing the kinetic energy per unit mass of fluid associated with velocity fluctuations, m^2/s^2 ; u' , v' , and w' are the fluctuating components of velocity in the x , y , and z directions, respectively, referring to the deviations from the mean velocity, m/s; The overline symbol $\overline{(\)}$ denotes the time averaged value.

Upon impacting the wall, the water decelerates and forms localized high-pressure stagnation zones. Water exerts drag and lift forces on the abrasive particles, inducing both translational and rotational motion, while the abrasives simultaneously transfer momentum back to the fluid. Jet kinetic energy is dissipated through the fluid shear and inter-particle collisions. For hard rock, abrasive impacts on the wall surface induce rock damage and material removal (Li et al., 2022; Qu et al., 2022b). Since the model assumes fixed walls, neglecting the effect of instantaneous rock breakage on the flow field, potential rock breaking behavior is indirectly assessed by analyzing the force exerted on the wall. The wall normal force and wall tangential force refer to the

components of the contact force exerted by particles on the wall surface, decomposed along the normal and tangential directions at the point of contact (Fig. 1). The wall normal force F_n and wall tangential force F_t are defined as follows:

$$F_n = k_n \delta_n - \gamma v_n \quad (5)$$

$$F_t = \min(k_t \delta_t - \gamma v_t, \mu F_n) \quad (6)$$

where, F_n is the normal force acting perpendicular to the wall surface, resisting particle penetration. It consists of an elastic restoring force and a damping force, N; F_t is the tangential force acting parallel to the wall surface, governed by elastic tangential response and limited by Coulomb friction, N; k_n and k_t are the normal and tangential contact stiffnesses. Based on the Hertz-Mindlin contact model, they are automatically calculated from the elastic modulus, Poisson's ratio, and particle radius, N/m; δ_n is the normal overlap (depth of contact), m; δ_t is the tangential displacement (sliding distance), m; γ is the coefficient of restitution, kg/s; v_n and v_t are the normal and tangential relative velocities between the particle and the wall, m/s; μ is the coefficient of friction.

2.2. Geometry and mesh structure

Fig. 2(a) presents the slot profile produced in hard rock by an abrasive water jet (AWJ) with a reciprocating nozzle. In conventional casing cementing, the AWJ must first penetrate the casing and then break the rock to form perforations. However, as the casing is close to the nozzle and only about 10 mm thick, it is relatively easy to penetrate (Surjaatmadja et al., 2009). At a jet velocity of 220 m/s, it can be penetrated within 1 min (Liu et al., 2023). In contrast, forming perforations in the rock takes significantly longer due to jet attenuation. Therefore, this study focuses on the flow behavior within the rock slot, and the influence of casing is not considered.

Based on the AWJ rock slotting experiment described in Section 2.3, a numerical model was developed to simulate the fluid-solid coupling among water, abrasives, and the wall in the slot. Fig. 2(b) depicts the model geometry with three components: ① the jet chamber, ② the annulus, and ③ the slot. ① The jet chamber represents the linear section at the exit of the abrasive water jet nozzle. It was modeled as a cylinder with a diameter and height of 2 mm. Considering both numerical convergence and computational efficiency, a nozzle with an outlet diameter of 2 mm was selected, which falls within the typical range of nozzle sizes. Moreover, the simulation results conform to the principle of geometric similarity, indicating that the conclusions of this study are applicable to nozzles of different diameters. The abrasive-water mixture was injected vertically downward through the top surface of the jet chamber, which was defined as the velocity inlet. The abrasive size, abrasive volume concentration, and jet velocity were consistent with the experimental parameters specified in Section 2.3. Spherical abrasive particles with a diameter of 200 μ m were used, and the abrasive volume concentration (abrasive volume/total jet volume) was set to 6%. Due to incomplete acceleration under practical conditions, a velocity difference exists between the abrasives and the water. In this simulation, the abrasive acceleration efficiency was assumed to be 80%. For example, when the jet velocity was 200 m/s, the corresponding abrasive injection velocity was set to 160 m/s. ② The annulus had a keyway-shaped cross-section, with its boundary extending 4 mm beyond the slot's top surface. Its height was defined by the jet distance. The top surface and lateral boundaries of the annulus were set as pressure outlets, with the outlet pressure specified as

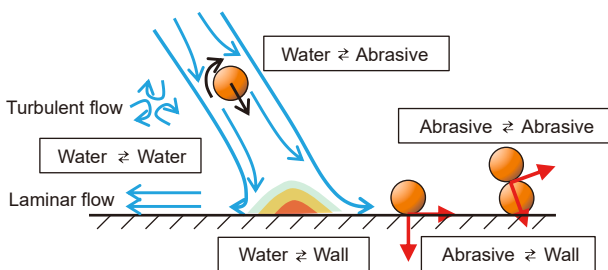


Fig. 1. Schematic diagram of force interactions in the fluid-solid coupling process among water, abrasives, and the wall.

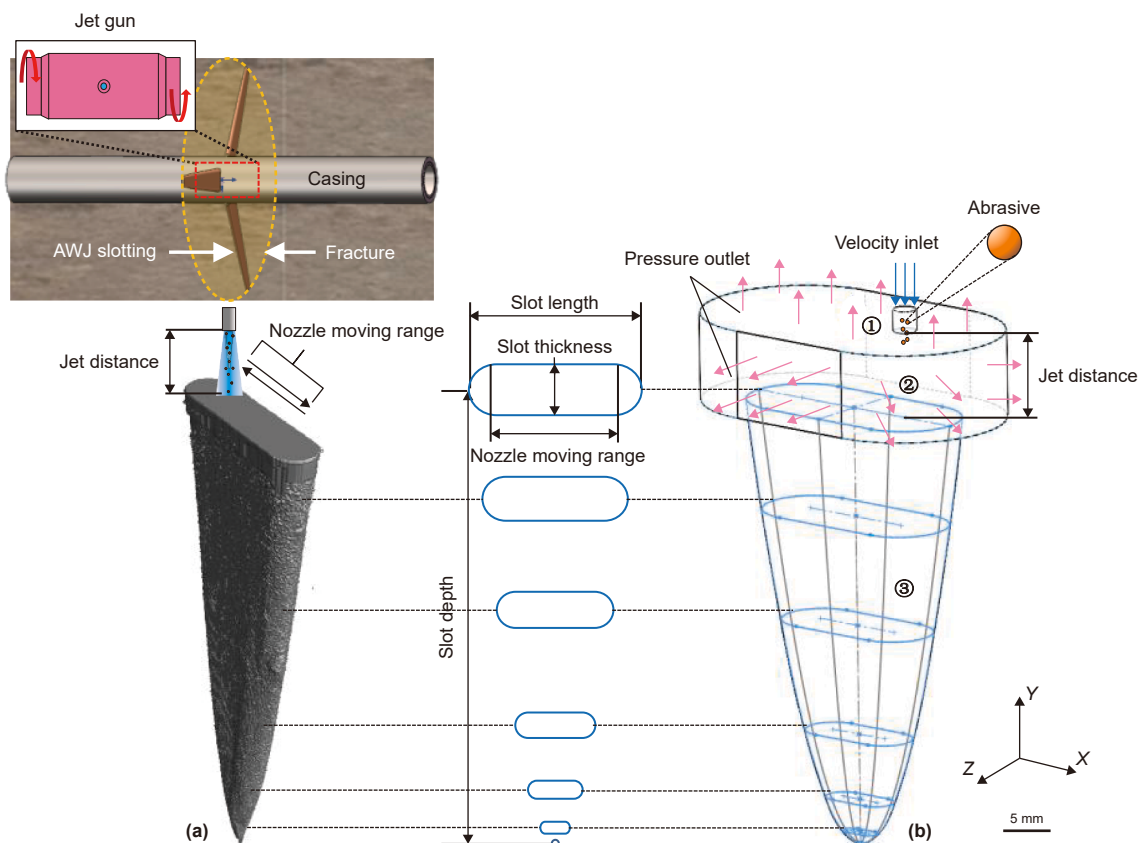


Fig. 2. Numerical model of fluid-solid coupling among water, abrasives, and wall in the slot. (a) CT scan of AWJ slotting after laboratory experiment (Section 2.3), (b) geometric structure of the model.

atmospheric pressure (101.3 kPa). ③ The slot exhibits a sword-shaped profile with a keyway-like cross-section. Its geometric characteristics include length, thickness, and depth. Slot length refers to the maximum extent along the slotting direction, slot thickness to the maximum span perpendicular to the slotting direction, and slot depth to the vertical distance from the top surface to the deepest point of the slot. As shown in Fig. 7(a), the slot depth increases with jet time but exhibits a decelerating growth trend over time. As shown in Fig. 7(b), the slot thickness is typically 4–5 times the nozzle outlet diameter. Slot length equals the nozzle moving range plus the slot thickness. The slot geometry of the model was generated by smoothly connecting keyway-shaped contours of varying depths. The slot thickness was set to 10 mm, equivalent to 5 times the nozzle outlet diameter. All remaining surfaces, except the velocity inlet and pressure outlets, were defined as wall boundaries. Table 1 presents the material parameters used in the model, as referenced from Baldini et al. (2018).

Due to the structural complexity of the model, mosaic meshing technology was employed (Fig. 3) (Peric and Ferguson, 2005). This polyhedron-based meshing approach automatically partitions complex geometries into high-quality polyhedral cells, enabling efficient and accurate discretization. A poly-hexcore meshing strategy was used, in which polyhedral cells were applied near boundaries and hexahedral cells filled the interior regions. The mesh feature size was set to 0.3 mm, and ten boundary layer meshes were applied. For the case with a slot length of 22 mm and a slot depth of 40 mm, a total of 530,882 cells were generated. This meshing configuration effectively balances computational efficiency with solution accuracy.

A transient simulation approach was employed, with a time step of 1 μ s, determined based on mesh size and flow rate to

Table 1
Model material parameters.

Physical properties	Parameters
Water density, kg/m ³	998.2
Water viscosity, kg/(m·s)	1.003×10^{-3}
Abrasive density, kg/m ³	3800
Abrasive poisson ratio	0.18
Abrasive shear modulus, GPa	38.14
Wall poisson ratio	0.18
Wall shear modulus, GPa	38.14
Coefficient of restitution	0.7
Coefficient of static friction	0.5
Coefficient of rolling friction	0.01

ensure computational stability and convergence. As shown in Fig. 4, the effect of jet time on the simulation results was examined using the case with a slot length of 22 mm and a slot depth of 40 mm as an example. Abrasive water jet slotting is a continuous and stable process, and flow field fluctuations were observed during the initial 2 ms. To ensure result stability, the flow field at 6 ms was selected to represent the state corresponding to the given slot shape. Furthermore, the actual nozzle movement and the slot shape changes during the 6 ms simulation were negligible. Therefore, employing a fixed geometry in the simulation was deemed appropriate.

2.3. Model validation

The AWJ rock slotting experiment provided parameters for the simulation and served as a basis for model validation. As shown in

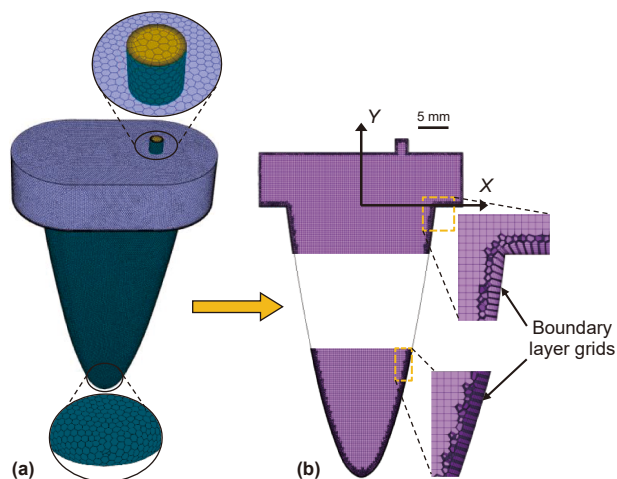


Fig. 3. Mesh configuration of the model. (a) Surface mesh, (b) volume mesh.

Fig. 5(a), the AWJ cutting system was employed in both the rock perforation and slotting experiments. The air compressor simply filled the pipe with abrasive. The high-pressure plunger pump acted as the power source of the jet. The control unit enabled automatic operation of both the high-pressure plunger pump and the mobile unit. The nozzle outlet diameter was 1 mm. The jet velocity was set to 200 m/s. Garnet was used as the abrasive material, with an average particle size of 200 μm . The abrasive volume concentration was 6%. As shown in Fig. 5(b) and (c), the jet

distance was 4 mm, the nozzle movement range was 20 mm, and the reciprocating movement rate of the nozzle was 100 mm/min. The samples were made of dense sandstone, a type of hard rock, and were machined into cubes with a side length of 100 mm. This dense sandstone has a density of 2.67 g/cm³, a uniaxial compressive strength of 160.6 MPa, an elastic modulus of 26.0 GPa, and a Poisson's ratio of 0.25.

The simulation results were compared with experimental data to validate the model in terms of both flow field characteristics and rock-breaking efficiency. Fig. 6 compares the flow field characteristics at different nozzle positions. As the nozzle moved closer to one side of the slot, the backflow converged from two streams into one. The experimental and simulation results show good agreement.

As shown in Fig. 7, the efficiency of AWJ rock perforation and slotting was compared experimentally, and the combined simulation results verified that the model effectively captures the mechanism of AWJ rock slotting. Fig. 6(d) and (e) present the perforation and slotting results at different jet time, while Fig. 7(a–c) provide a statistical analysis of the corresponding hole shape parameters. As shown in Fig. 7(a), AWJ rock slotting reached a depth of 70 mm in 40 s, whereas AWJ rock perforation required 4.5 times longer to achieve the same depth. Fig. 7(c) shows that the rock breaking rate of slotting is 64.5 mm³/s, which is 12 times higher than that of perforation at 5.4 mm³/s. Fig. 7(d) and (e) compare the abrasive velocity distribution and wall normal force distribution between perforation and slotting at the same hole depth. Fig. 7(d) shows that a significant amount of abrasive accumulates at the bottom of the perforation, hindering direct jet

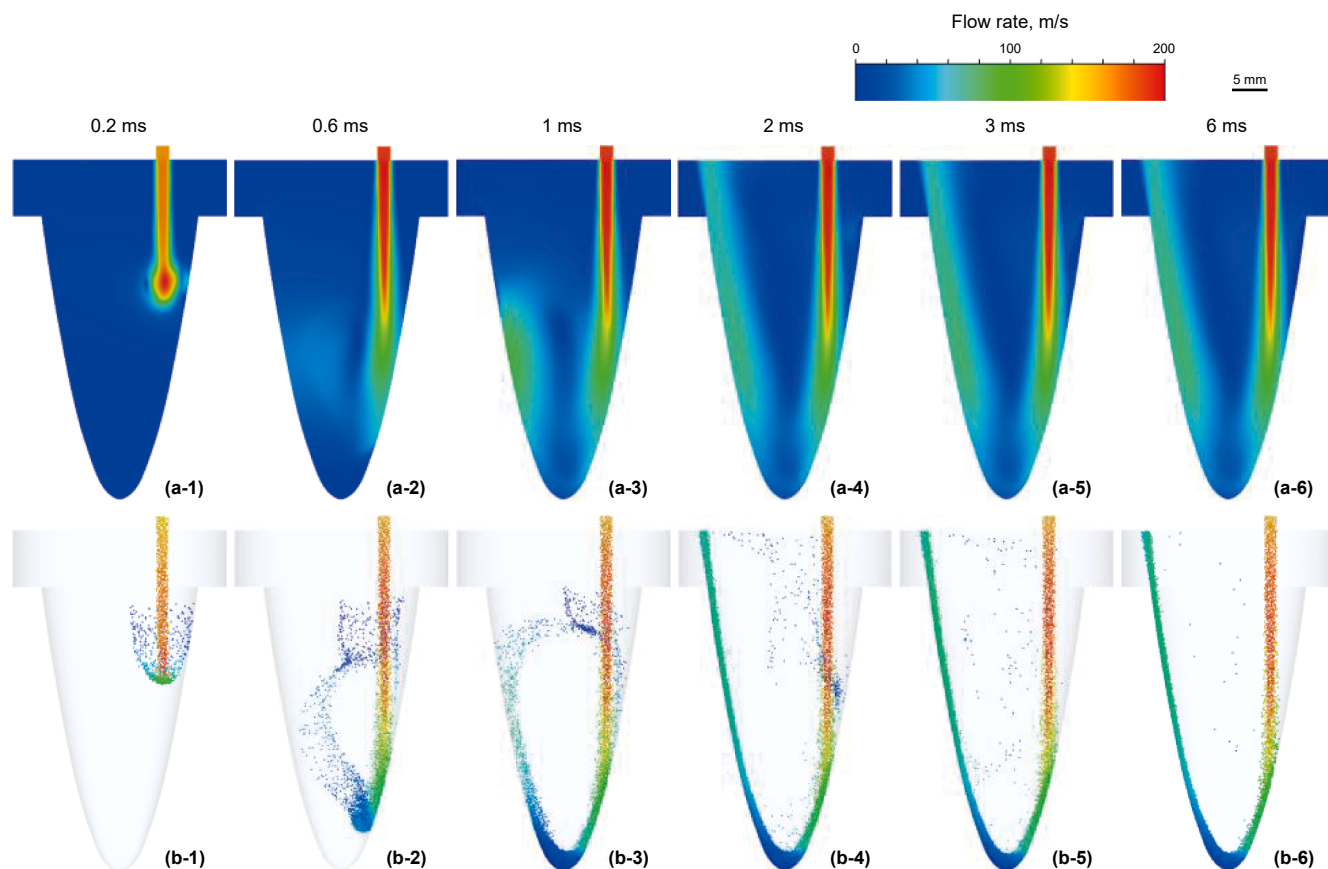


Fig. 4. Flow field evolution of water and abrasives over transient simulation time. (a-1, a-2, a-3, a-4, a-5, a-6) Contour plots of water flow rate, (b-1, b-2, b-3, b-4, b-5, b-6) spatial distribution of abrasive velocity.

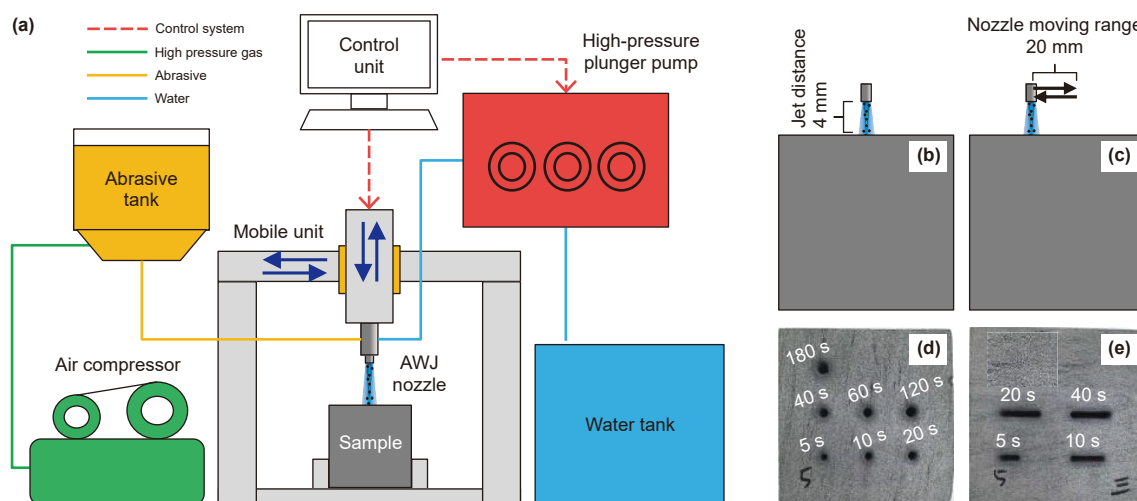


Fig. 5. AWJ rock slotting experiments. (a) AWJ cutting system, (b) AWJ rock perforation, (c) AWJ rock slotting, (d) rock after perforation, (e) rock after slotting.

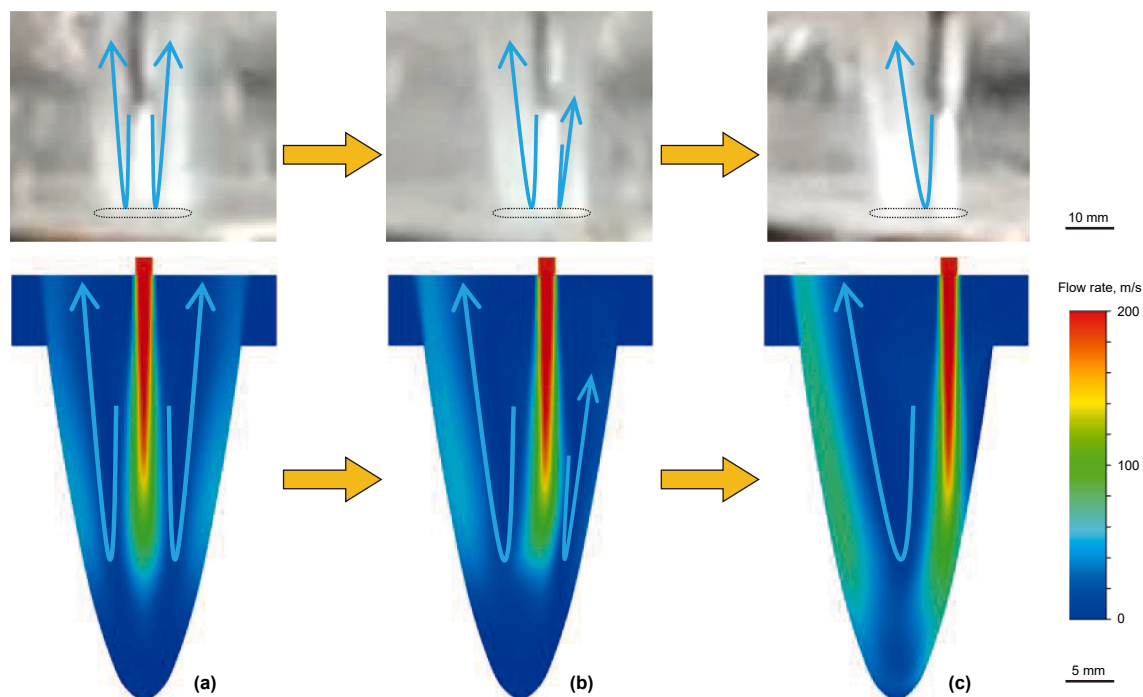


Fig. 6. Backflow characteristics from experiments and simulations at different nozzle positions. (a) 1/2 nozzle moving range, (b) 3/4 nozzle moving range, (c) full nozzle moving range.

impact on the rock, whereas no substantial accumulation is observed at the bottom of the slot. Correspondingly, Fig. 7(e) indicates that the wall normal force in the slotting case is approximately 10 times greater than that in the perforation case, which aligns with the experimentally observed rock breaking efficiency. These results validate the model and demonstrate its capability to reveal the mechanism of AWJ rock slotting.

Table 2 outlines the simulation schemes and includes variables such as nozzle position, slot geometry, and jet parameters. Cases 1–3 were designed to investigate the influence of nozzle position on flow characteristics within the slot and the resulting wall force

distribution, as presented in Section 3.1. As jet time increases and the nozzle advances, the slot length and depth continue to increase, while the slot thickness remains nearly constant (Fig. 7(a) and (b)). Slot length and depth were selected as the main variables, and to quantitatively examine their effects on in-slot flow, a research strategy was adopted in which the two parameters were varied independently. Specifically, Cases 4, 5, 3, and 6 were used to assess the influence of slot length (Section 3.2.1), whereas Cases 7, 3, and 8 focused on the effect of slot depth (Section 3.2.2). Jet parameters are also critical to the slotting process. Specifically, Cases 9, 3, and 10 were designed to study the effect of jet velocity

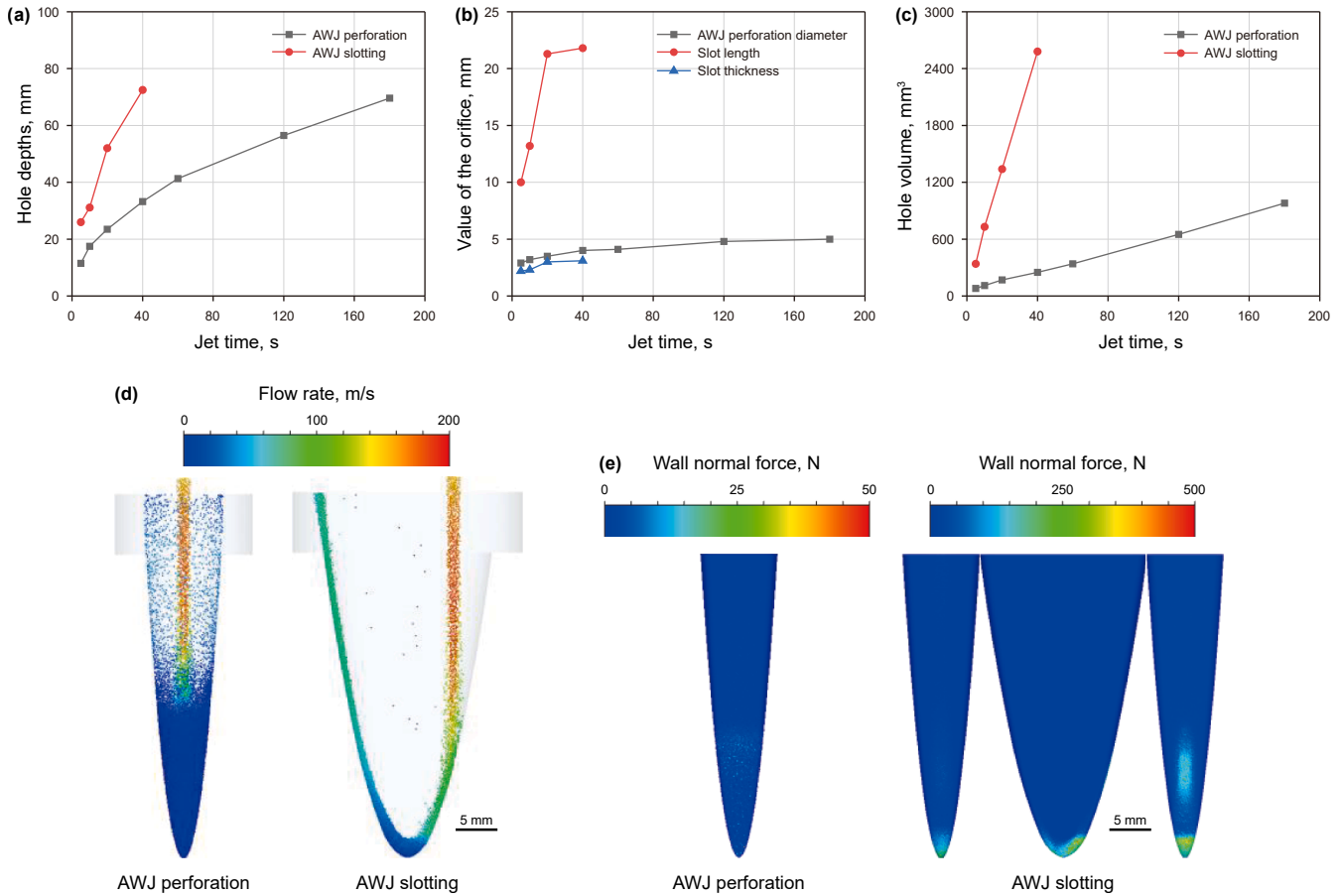


Fig. 7. Comparison between AWJ rock perforation and slotting. (a) Experimentally measured hole depth, (b) experimentally measured orifice size, (c) experimentally measured hole volume, (d) abrasive velocity distribution from simulation (Case 4 and Case 1), (e) wall normal force distribution from simulation (Case 4 and Case 1).

Table 2
Simulation scheme.

Case	Nozzle moving range, mm	X-direction coordinate of the nozzle, mm	Slot length, mm	Slot depth, mm	Jet velocity, m/s	Jet distance, mm
1	12	0	22	40	200	8
2	12	3	22	40	200	8
3	12	6	22	40	200	8
4	0	0	10	40	200	8
5	4	2	14	40	200	8
6	20	10	30	40	200	8
7	12	6	22	20	200	8
8	12	6	22	60	200	8
9	12	6	22	40	150	8
10	12	6	22	40	250	8
11	12	6	22	40	200	16
12	12	6	22	40	200	24

(Section 3.3.1), while Cases 3, 11, and 12 investigated the influence of jet distance (Section 3.3.2).

3. Simulation results

3.1. Internal flow field and particle-wall force distribution

3.1.1. Flow characteristics of water

As shown in Fig. 8, as the nozzle approaches the end of the slot, the fluid in the slot becomes increasingly convergent, leading to greater energy concentration. As shown in Fig. 8(a), three types of flow were observed in the slot: inflow, backflow, and suction flow.

The inflow refers to the high-velocity jet discharged from the nozzle toward the slot bottom. Backflow is the fluid that returns from the slot bottom to the annulus, flowing along both ends of the slot. As shown in Fig. 8(d), due to the abrupt change in jet flow direction after impacting the slot bottom, a region of very low flow velocity develops. The suction flow primarily consists of fluid drawn into the slot from the annulus, induced by the high-velocity inflow. This fluid becomes entrained and swirls in the region between the inflow and the backflow. When the nozzle was positioned at the center of the slot, two backflows formed on either side, exhibiting comparable flow rates (Fig. 8(a) and (d)). As the nozzle moved to the right, the backflow on the left side intensified,

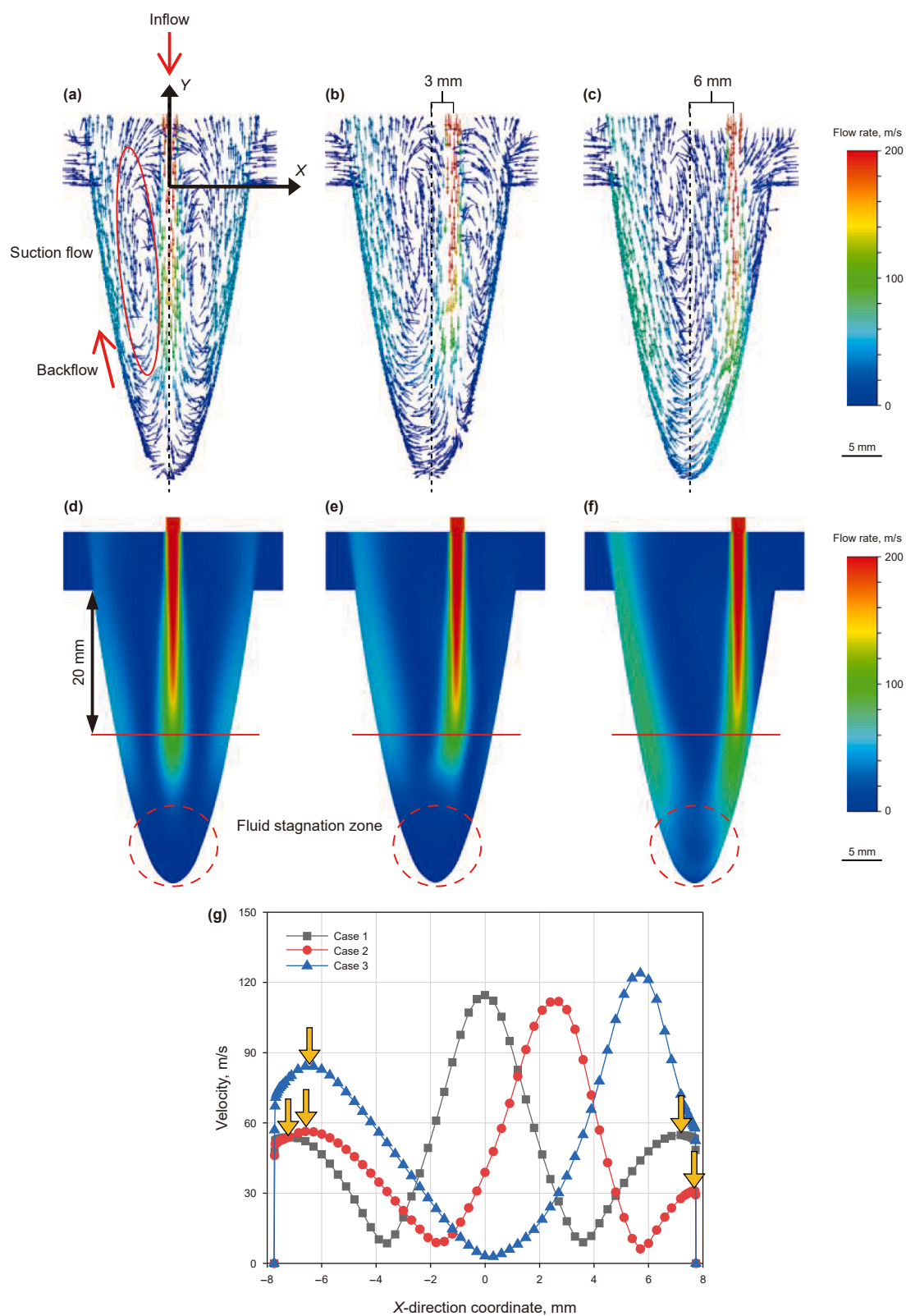


Fig. 8. Characteristics of water flow rate at different nozzle positions in Case 1, Case 2 and Case 3. (a–c) Vector diagrams of water flow rate, (d–f) contour plots of water flow rate, (g) distribution of water flow rate at a depth of 20 mm.

while the backflow on the right side weakened (Fig. 8(b) and (e)). When the nozzle was positioned 6 mm away from the center, the right-side backflow nearly disappeared, while the left-side backflow increased significantly (Fig. 8(c), (f), and (g)). At this point, a certain flow rate was still maintained at the slot bottom.

The flow rate distribution in the slot and its evolution due to nozzle movement are influenced by turbulence effects. The extent of jet kinetic energy dissipation due to turbulence was assessed by examining the distribution of turbulent kinetic energy, which represents the energy associated with velocity fluctuations in the flow (Eq. (4)). Higher turbulent kinetic energy indicates more intense velocity variations and stronger turbulence within the flow field. Turbulent action is linked to the fluid velocity gradient, which depends on the magnitude of the velocity difference and the distance over which this change occurs. Fig. 9(a–c) show that turbulence primarily occurs in the suction flow region mentioned in Fig. 8. The closer the flow is to the inflow and backflow zones, the more pronounced the turbulence effects become. Furthermore, as the slot depth increases and the cross-sectional area narrows, turbulence intensifies. As shown in Fig. 9(d), as the nozzle moved to the right, the turbulent effects on the left weakened, while those on the right intensified. This helps explain the variation in flow rate observed in Fig. 8.

The jet impact process often results in increased pressure within the hole (Liu et al., 2025b). The fluid flow in the slot is accompanied by pressure generation, and the resulting pressure distribution in turn influences the flow behavior. As shown in Fig. 10(a–c), a high-pressure region is observed at the bottom of the slot, corresponding to the fluid stagnation zone mentioned in Fig. 8. Fig. 10(d) indicates that the slot contains distinct low-pressure, transition, and high-pressure regions. When the nozzle was positioned at the center or 3 mm away from the center, the maximum pressure in the slot was approximately 3 MPa. However, when the nozzle was positioned 6 mm from the center, the maximum pressure increased to around 6 MPa. The higher pressure at the slot bottom facilitates the acceleration of backflow, which helps explain why the backflow rate on the left side in Case 3 is higher than in Cases 1 and 2 (Fig. 8(g)).

3.1.2. Velocity distribution of abrasive particles

The variation in abrasive velocity is influenced by both the water flow field distribution and the abrupt deceleration upon impact with the wall surface. As shown in Fig. 11, the abrasive motion closely mirrors that of the water, exhibiting distinct inflow and backflow behaviors mentioned in Fig. 8. As the nozzle gradually approaches the end of the slot, the backflow abrasives accumulate progressively, and their kinetic energy increases accordingly (Fig. 11(b), (e), and (h)). Fig. 11(c), (f), and (i) show the instantaneous velocities of abrasive particles, where each scatter point represents a single particle. As shown in Fig. 11(c), based on the velocity distribution patterns, four characteristic regions are identified: the stable zone, the inflow deceleration and backflow acceleration zone, the turning zone, and the sand pad. When the nozzle was centered, abrasives returned symmetrically from both sides with comparable velocities (Fig. 11(a) and (b)). As the nozzle shifted to the right, the quantity and velocity of abrasives returning from the left increased, while those from the right diminished (Fig. 11(d) and (e)). As seen in Fig. 11(c) and (f), the velocity of the primary inflow abrasives gradually decreased beyond a depth of 15 mm due to the attenuation of water flow. These particles then impacted the sand pad and came to a stop, before being re-accelerated by the backflow and transported back to the annulus. When the nozzle was positioned 6 mm off-center, the inflow abrasives impacted the right wall, and all abrasives subsequently returned from the left side (Fig. 11(g) and (h)). As shown in

Fig. 11(i), the primary inflow abrasives began to decelerate at a depth of approximately 17 mm, collided with the right wall near a depth of 30 mm, and then continued descending toward the slot bottom. They were then re-accelerated by the backflow and transported back to the annulus. When the nozzle was positioned at the center of the slot or 3 mm off-center, a noticeable accumulation of abrasives formed at the slot bottom. In contrast, this accumulation was almost entirely absent when the nozzle was displaced by 6 mm.

3.1.3. Particle impact on the wall surface

Previous studies have demonstrated that impact-induced abrasion by abrasive particles is the dominant mechanism for rock material removal, significantly outweighing the effect of water, particularly when processing harder rocks (Li et al., 2022; Qu et al., 2022b). Fig. 12 illustrates the forces exerted by abrasive particles on the wall surface elements at different nozzle positions. The normal and tangential forces are the two primary components describing the contact interaction between the particles and the wall, as defined in Eqs. (5) and (6). The normal force acts perpendicular to the contact surface, while the tangential force represents the frictional component acting parallel to the surface. Each data point in the scatter plot represents the cumulative force experienced by a wall element at a specific location. A comparison of the normal and tangential force distributions in Fig. 12 reveals notable similarities, indicating that these two force components commonly occur simultaneously during particle-wall interactions. As shown in Fig. 12(a), (c), and (e), the peak forces on the wall surface are concentrated near the slot bottom and progressively shift to the right as the nozzle moves in that direction. The concentrated force regions observed at the bottom in Cases 1 and 2 (Fig. 12(a) and (c)) correspond to the turning zone identified in Fig. 11. In this zone, abrasives undergo a primary impact upon initial contact with the wall surface, followed by a secondary impact after re-acceleration by the water flow. The force associated with the secondary impact is lower than that of the primary impact. In Case 3 (Fig. 12(e)), the concentrated force region corresponds to three distinct impact events illustrated in Fig. 11: the initial impact on the right wall, a secondary impact as the particle continues toward the bottom, and a tertiary impact upon returning after being re-accelerated by the backflow. Although the abrasive velocity during the first impact is higher, the impact angle significantly influences the resulting force magnitude. As a result, the second impact produces a greater force than the first. Moreover, the overall force exerted on the wall surface in Case 3 is substantially greater than that in Cases 1 and 2. Due to the high similarity between the distributions of wall normal force and wall tangential force, only the wall normal force is analyzed in the subsequent results, while the wall tangential force is omitted.

3.2. Effect of slot shape evolution on water-abrasive-wall interaction

3.2.1. Effect of slot length

As shown in Fig. 13, increasing the slot length results in a larger cross-sectional area, which diminishes turbulence intensity within the slot and enables more of the jet's kinetic energy to be preserved. Fig. 13(a-1) shows that when the hole cross-section is relatively small, the maximum turbulent kinetic energy can reach up to $2000 \text{ m}^2/\text{s}^2$. When the slot length is extended to 14 mm, the maximum turbulent kinetic energy decreases to $1000 \text{ m}^2/\text{s}^2$ (Fig. 13(a-2)). As shown in Fig. 13(b-1), (b-2), (c-1), and (c-2), when the slot length is relatively short, significant water and sand pads form at the slot bottom, severely hindering the direct impact of

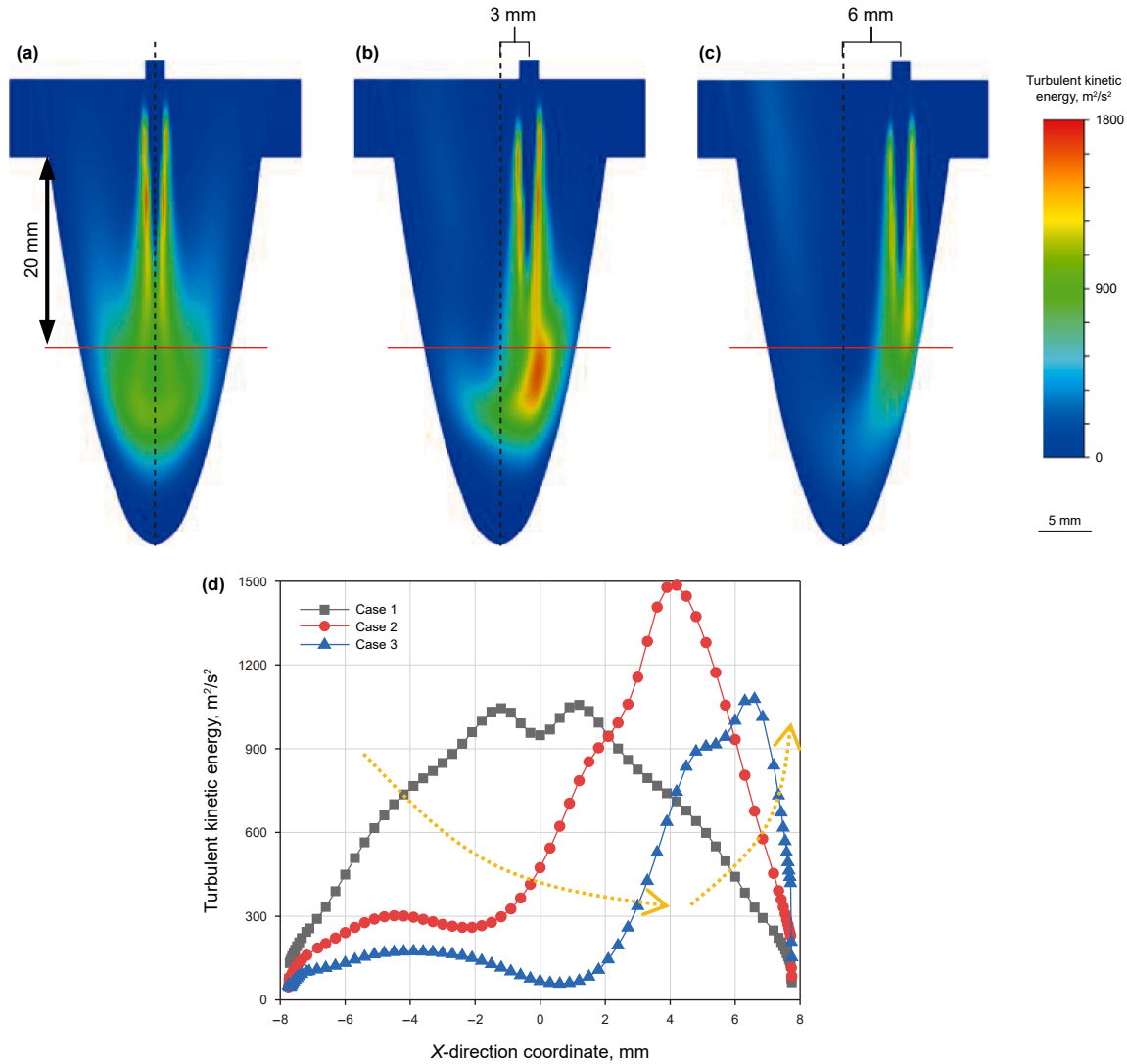


Fig. 9. Characteristics of water turbulent kinetic energy at different nozzle positions in Case 1, Case 2 and Case 3. (a–c) Contour plots of water turbulent kinetic energy, (d) distribution of water turbulent kinetic energy at a depth of 20 mm.

abrasives on the wall. As shown in Fig. 13(b-3), (b-4), (c-3), and (c-4), as the slot length further increases, the water and sand pads nearly disappear. Fig. 14 further compares the distributions of abrasive velocity and wall force for slot lengths of 10 and 30 mm. As illustrated in Fig. 14(a), for a slot length of 10 mm, the inflow abrasives experienced early deceleration due to the attenuation of water velocity, which led to a short stopping distance and the formation of a thick sand pad. In contrast, for a slot length of 30 mm, little to no sand pad formation was observed, as shown in Fig. 14(b). Moreover, the inflow abrasive velocity near the turning zone reached approximately 30 m/s in Case 4, compared to about 80 m/s in Case 6. Since abrasive velocity directly influences the impact force exerted on the wall surface, the normal force in Case 6 exceeded that in Case 4 by more than two orders of magnitude, as shown in Fig. 14(c) and (d). The above analysis helps explain why AWJ rock slotting is significantly more effective than AWJ rock perforation, as demonstrated in Section 2.3.

3.2.2. Effect of slot depth

As shown in Fig. 15, increasing the slot depth extends the fluid's path influenced by turbulence, leading to greater dissipation of the jet's kinetic energy. As shown in Fig. 15((a-1)–(a-3)), with the

increase in the slot depth, the turbulence intensity does not change significantly, but the path of turbulence action becomes longer. When the slot depth reaches 60 mm, noticeable water and sand pads have already formed (Fig. 15(b-3) and (c-3)). Fig. 16 further compares the distributions of abrasive velocity and wall force for slot depths of 20 and 60 mm. As illustrated in Fig. 16(a), at a slot depth of 20 mm, the inflow abrasives maintained an average velocity of approximately 100 m/s near the turning zone, with virtually no sand pad formation. In contrast, at a slot depth of 60 mm, the primary inflow abrasives began decelerating at a depth of 16 mm and continued slowing until reaching the turning zone at 51 mm, where their average velocity dropped to around 30 m/s, as shown in Fig. 16(b). This velocity reduction significantly diminished the impact force. As depicted in Fig. 16(c) and (d), the wall normal force in Case 7 was over 40 times higher than that in Case 8.

3.3. Influence of jet parameters on water-abrasive-wall interaction

3.3.1. Effect of jet velocity

As shown in Fig. 17, increasing the jet velocity elevates the kinetic energy of the jet; however, it also amplifies turbulence within the slot, resulting in greater dissipation of energy. As shown

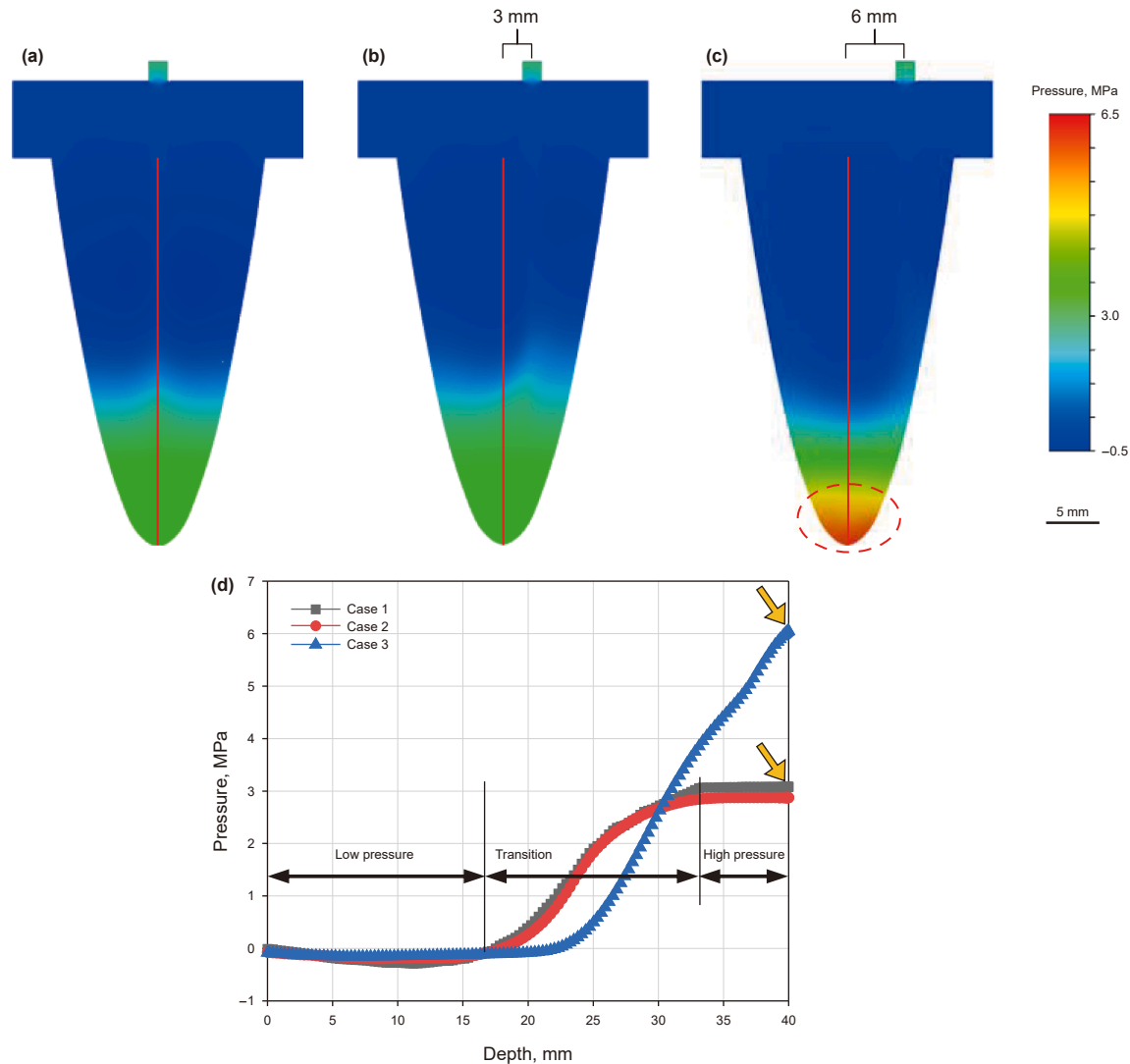


Fig. 10. Water pressure characteristics at different nozzle positions in Case 1, Case 2 and Case 3. (a–c) Contour plots of water pressure, (d) variation of water pressure along the central axis.

in Fig. 17((a-1)–(a-3)), increasing the jet velocity from 150 to 250 m/s raises the maximum turbulent kinetic energy from 1000 to 2600 m^2/s^2 . Despite this, the overall flow structure of both water and abrasives remains largely unchanged (Fig. 17((b-1)–(c-3))). Fig. 18(a) and (b) illustrate that when the jet velocity was increased from 150 to 250 m/s, the average velocity of the inflow abrasives near the turning zone rose from 60 to 80 m/s. Correspondingly, the normal force exerted on the wall surface increased by approximately 30%, as shown in Fig. 18(c) and (d).

3.3.2. Effect of jet distance

As shown in Fig. 19, increasing the jet distance does not significantly alter the intensity of fluid turbulence; however, it extends the path over which turbulence acts, resulting in greater dissipation of jet kinetic energy. As shown in Fig. 19((a-1)–(a-3)), with increasing jet distance, the turbulence intensity does not change significantly, but the path of turbulence action becomes longer. When the jet distance reaches 24 mm, noticeable water and sand pads have already formed (Fig. 19(b-3) and (c-3)). As illustrated in Fig. 20, when the jet distance increased from 8 to 24 mm, the average velocity of the inflow abrasives near the

turning zone decreased from 70 to 30 m/s, and the normal force exerted on the wall surface declined by approximately 90%. This indicates that an excessively large jet distance is detrimental to AWJ rock slotting.

4. Discussion

4.1. Water-abrasive-slot coupling mechanism

Slot formation is driven by the coupled and cumulative effects of fluid dynamics, abrasive motion, and material response (Fig. 1). In this study, to investigate the mechanism of abrasive water jet (AWJ) rock slotting, a coupled CFD-DEM fluid-structure interaction model was developed, incorporating water flow, abrasive particles, and slot geometry. The influences of nozzle position, slot length, slot depth, jet velocity, and jet distance were systematically analyzed. Based on the analysis of water turbulence, abrasive velocity distribution, and wall impact forces, insights into the coupling mechanism are provided in Fig. 21. The slot geometry influences water turbulence, which subsequently affects abrasive velocity. The velocity and trajectory of the abrasives, combined

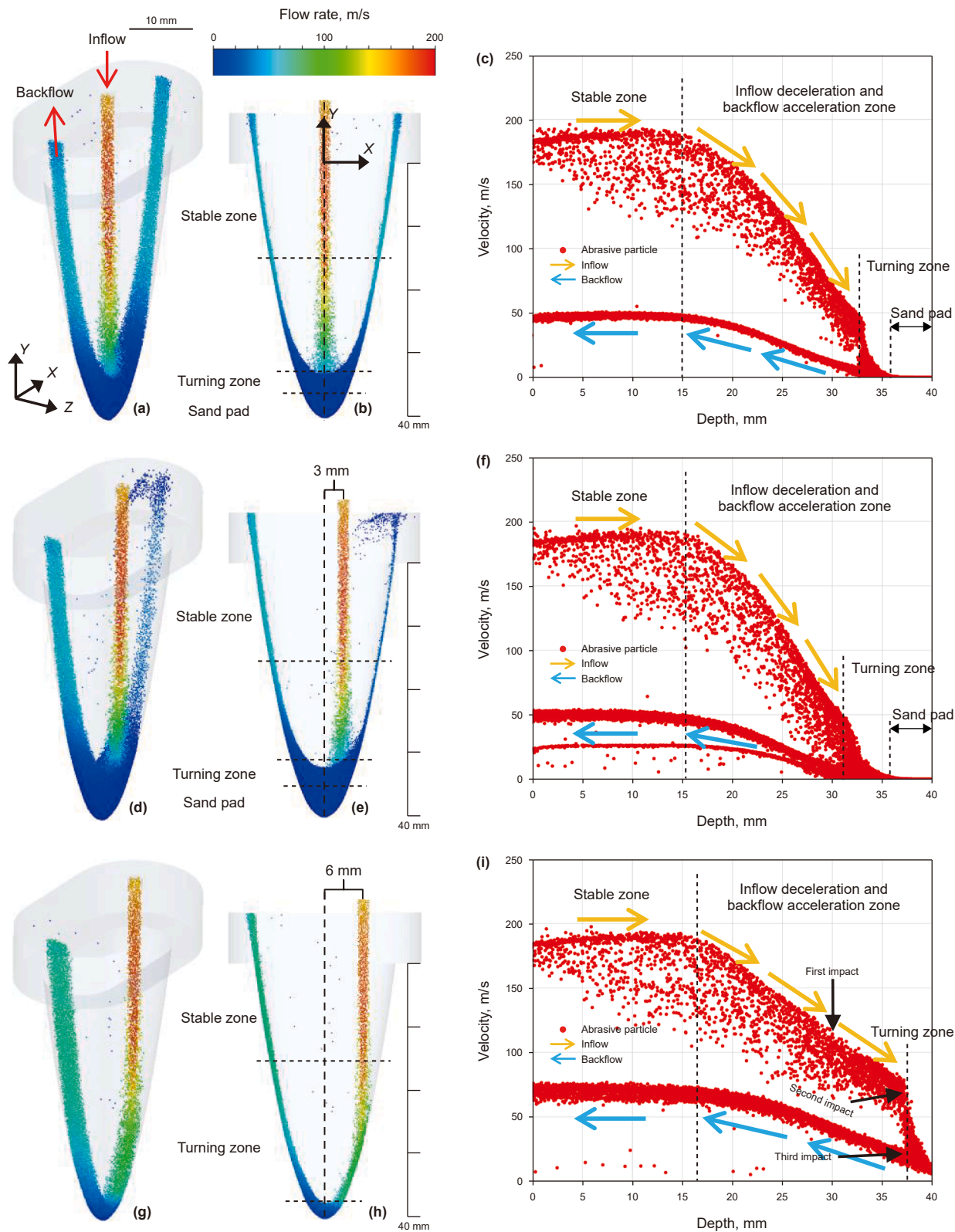


Fig. 11. Abrasive velocity distribution at different nozzle positions in Case 1, Case 2 and Case 3. (a, b, d, e, g, h) Spatial distribution of abrasive velocity, (c, f, i) variation of abrasive velocity with depth.

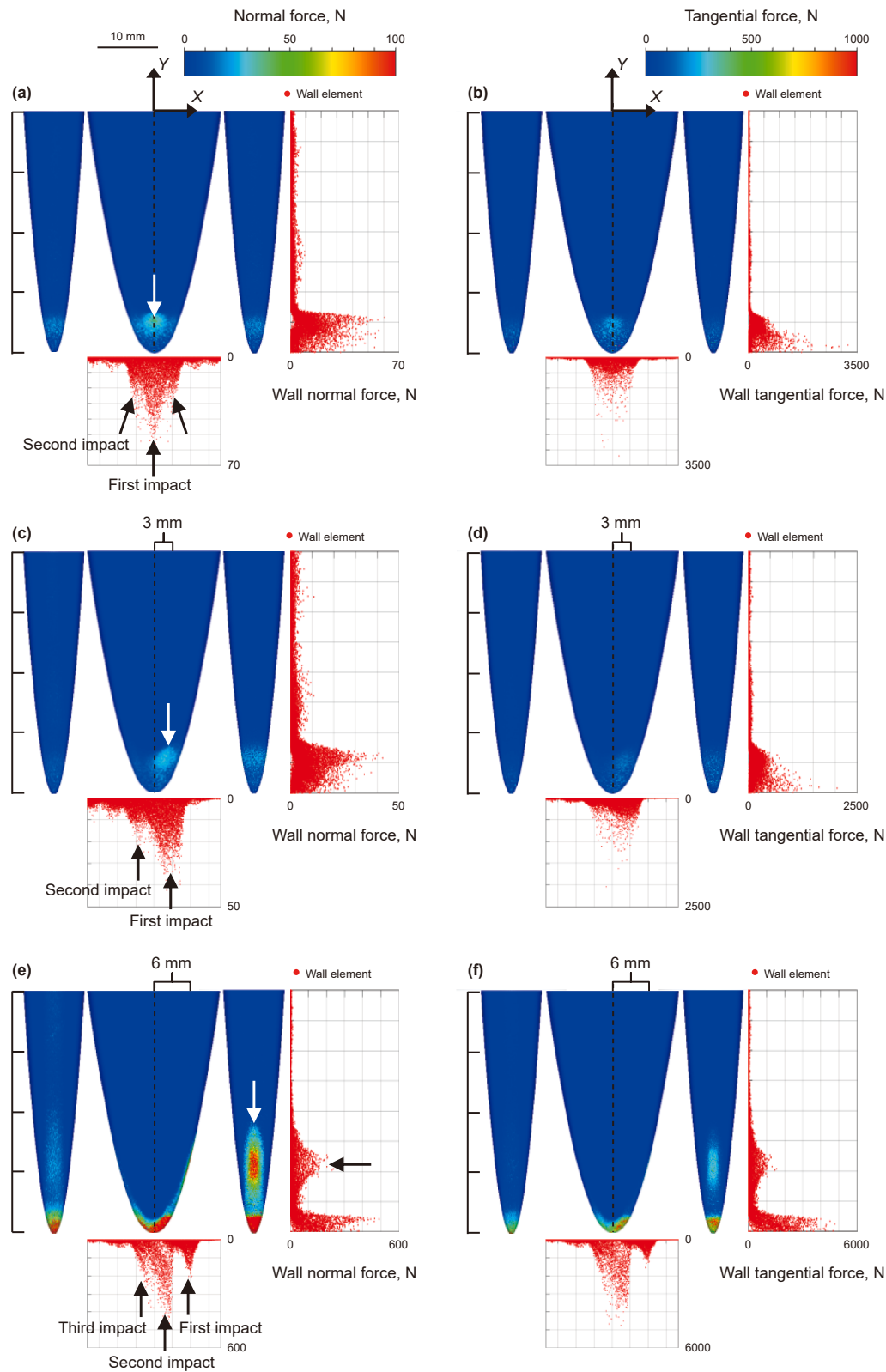


Fig. 12. Force distribution on rock wall surface elements at different nozzle positions in Case 1, Case 2 and Case 3. (a, c, e) Distribution of normal forces, (b, d, f) distribution of tangential forces.

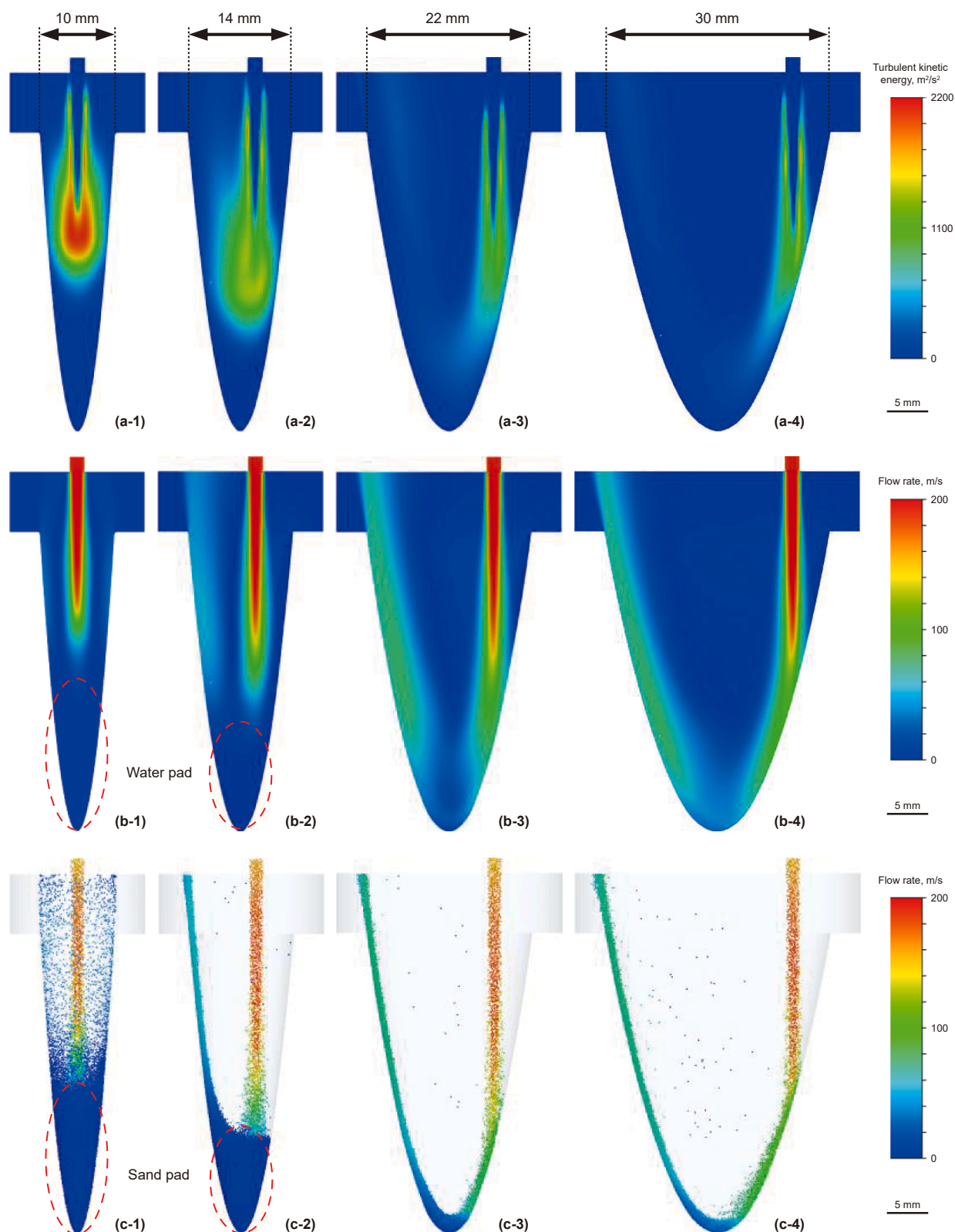


Fig. 13. Motion characteristics of abrasives and water at different slot lengths in Case 4, Case 5, Case 3 and Case 6. (a-1, a-2, a-3, a-4) Contour plots of water turbulent kinetic energy, (b-1, b-2, b-3, b-4) contour plots of water flow rate, (c-1, c-2, c-3, c-4) spatial distribution of abrasive velocity.

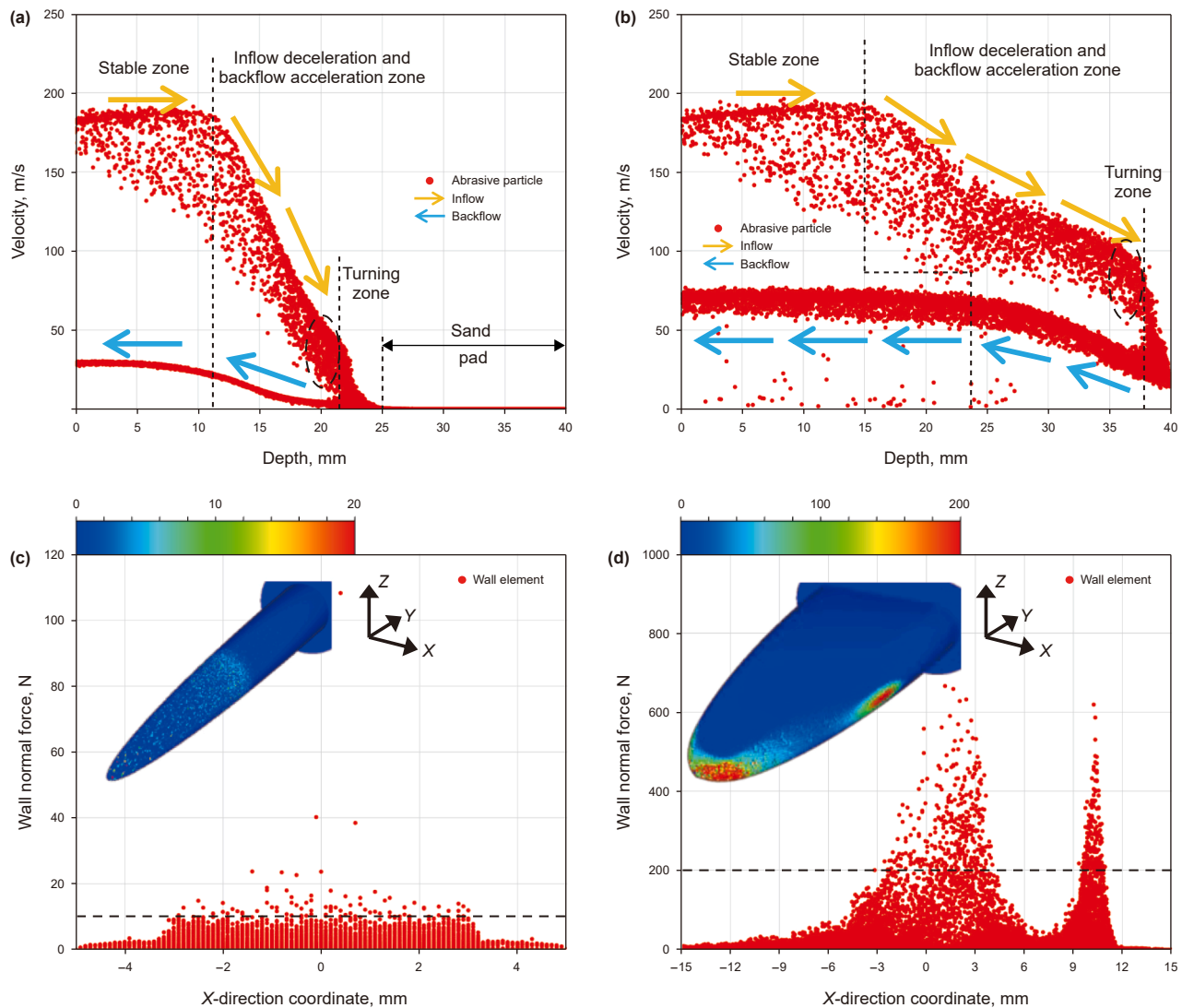


Fig. 14. Distribution of abrasive velocity and wall force in Case 4 with slot length of 10 mm and Case 6 with slot length of 30 mm. (a, b) Variation of abrasive velocity with depth, (c, d) distribution of wall normal force along the X-direction.

with the slot boundaries, determine the magnitude and distribution of abrasive impacts on the wall surface. Repeated high-frequency impacts cause surface erosion, gradually reshaping the slot geometry. These morphological changes, in turn, alter the internal flow field and abrasive acceleration, forming a dynamic and self-reinforcing feedback loop in which slot evolution continuously influences and is influenced by the in-slot flow behavior.

The radial dimension of the slot determines its cross-sectional area, which directly influences turbulence intensity. As shown in Section 3.2.1, increasing slot length expands the cross-sectional area, thereby reducing turbulence intensity and alleviating jet kinetic energy dissipation. This helps explain the experimental results in Section 2.3, where AWJ rock slotting demonstrated significantly higher rock breaking efficiency than AWJ rock perforation. As shown in Fig. 7(d) and (e), severe dissipation of jet kinetic energy results in the formation of water and sand pads at the hole bottom, which prevent abrasives from directly impacting the wall, thereby significantly reducing rock breaking efficiency. The axial dimension of the slot defines the turbulence-affected path length and governs the extent of kinetic energy loss. As

shown in Sections 3.2.2 and 3.3.2, increasing the slot depth and jet distance has minimal effect on turbulence intensity but extends the turbulence-affected path, thereby reducing the abrasive velocity near the wall surface and diminishing rock breaking efficiency. Fig. 7(a) shows that with increasing jet time, the depth growth of AWJ perforation slows down. Cai et al. (2019) reported similar experimental observations. However, since both slot length and depth increase simultaneously during AWJ slotting, its depth continues to grow at a relatively high rate. This indicates that while increasing slot depth, appropriately extending the slot length facilitates efficient rock breaking and deep penetration.

The velocity and trajectory of the abrasives, together with the local geometry of the slot boundaries, dictate the magnitude and distribution of abrasive impacts on the wall surface. For example, Fig. 11(i) and 12(e) show that abrasives during the first impact at a depth of 30 mm had higher velocities than those during the second impact at 37 mm. However, the second impact exerted a greater force due to a larger impact angle between the abrasive and the wall. Li et al. (2025) demonstrated that the extent of rock damage increases with larger particle size, higher jet impact velocity, and greater impact angle. This suggests that even with a decrease in

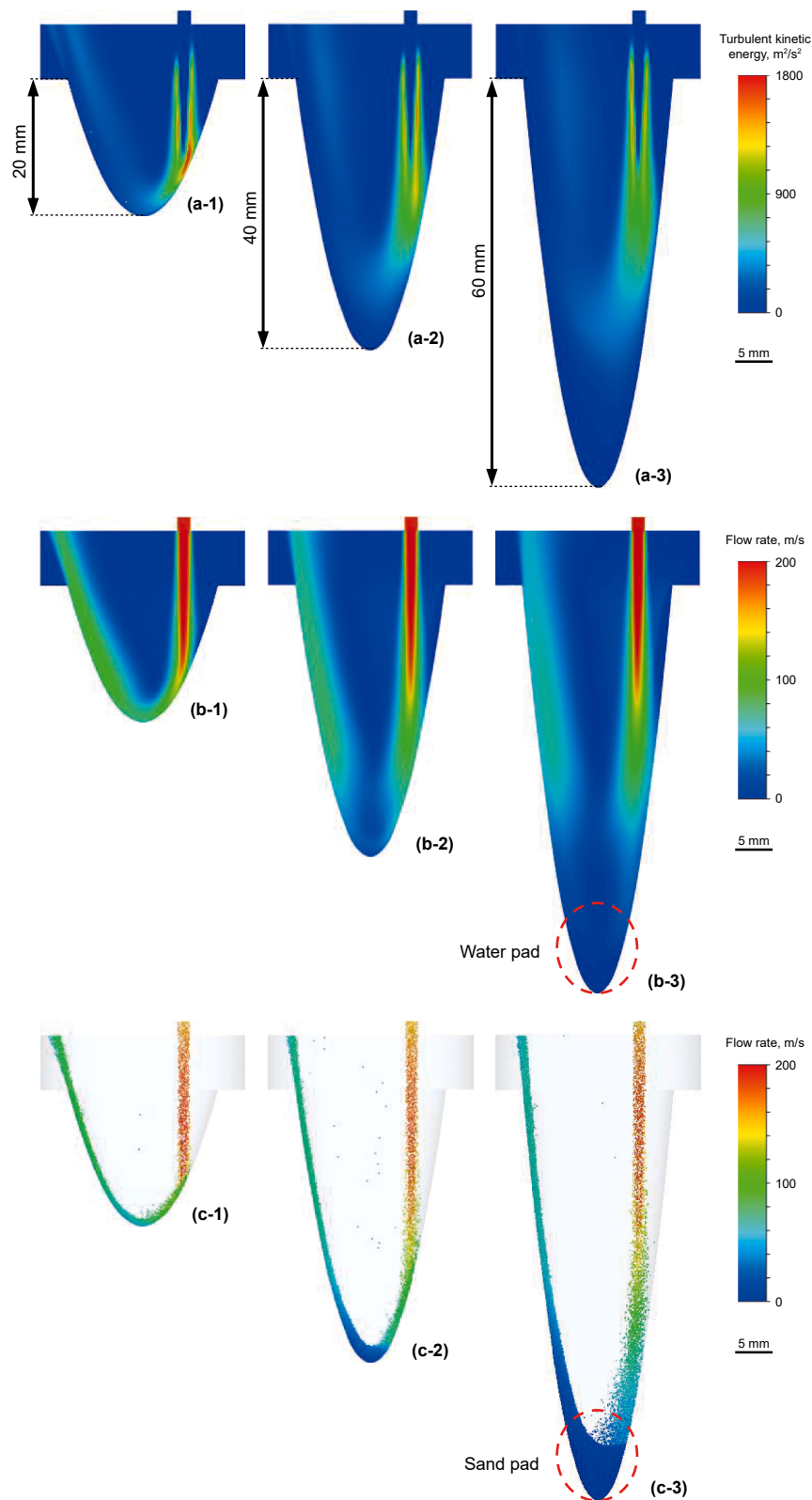


Fig. 15. Motion characteristics of abrasives and water at different slot depths in Case 7, Case 3 and Case 8. (a-1, a-2, a-3) Contour plots of water turbulent kinetic energy, (b-1, b-2, b-3) contour plots of water flow rate, (c-1, c-2, c-3) spatial distribution of abrasive velocity.

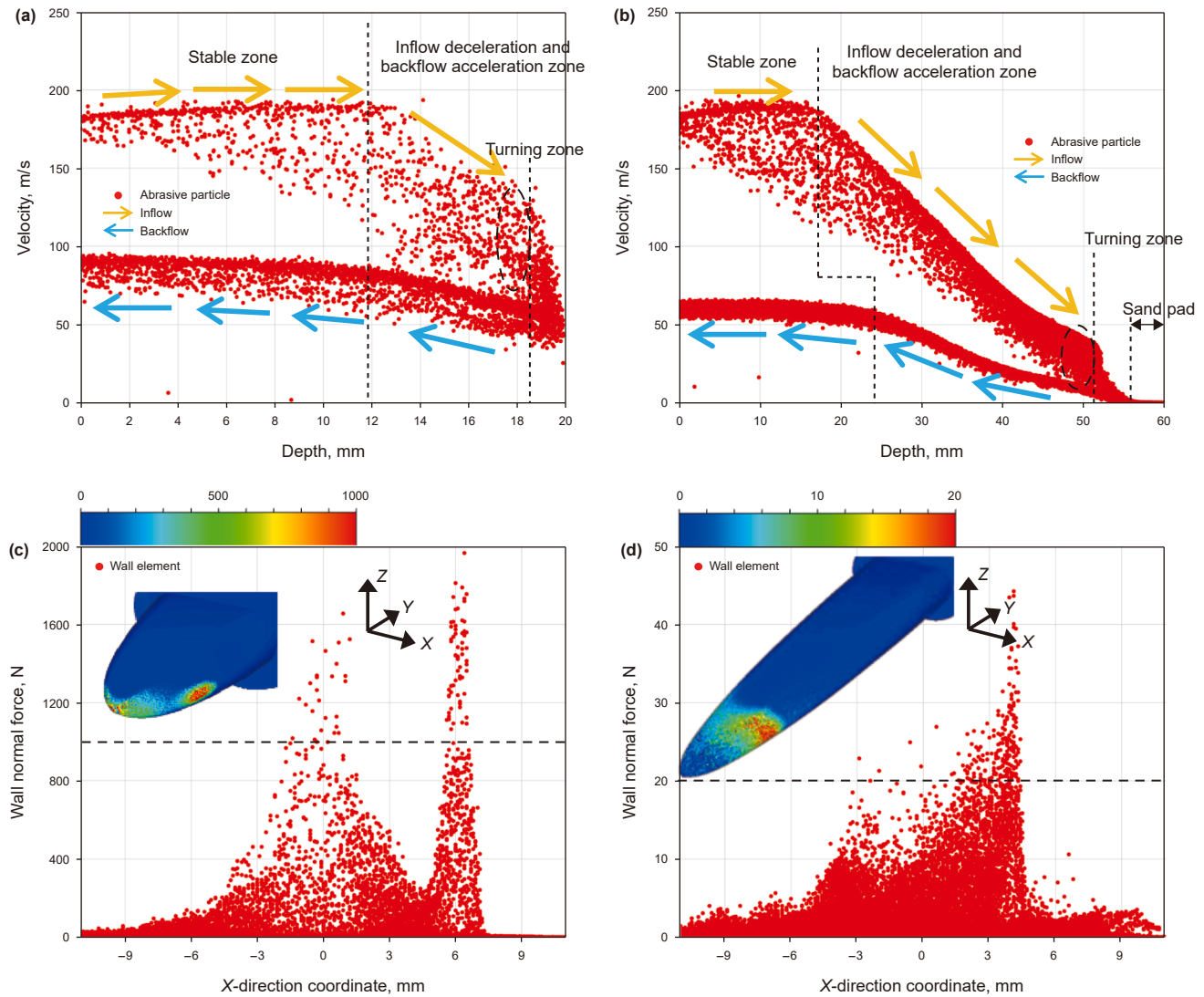


Fig. 16. Distribution of abrasive velocity and wall force in Case 7 with slot depth of 20 mm and Case 8 with slot depth of 60 mm. (a, b) Variation of abrasive velocity with depth, (c, d) distribution of wall normal force along the X-direction.

abrasive impact velocity, a larger impact angle can still improve the rock breaking efficiency. As shown in the experiments in Section 2.3, whether in perforation or slotting, the increase in depth is significantly greater than the change in diameter. This is primarily due to the turning zone at the bottom of the hole or slot, where abrasives impact the rock at angles close to 90° , resulting in a greater growth rate in depth. In contrast, diameter expansion is driven by the backflow abrasives, which, despite their relatively high velocity, strike the rock at shallow angles, leading to a much lower rock removal rate in the radial direction. Furthermore, a higher abrasive concentration does not necessarily lead to better performance. For example, Xu et al. (2025b) found experimentally that the optimal slotting performance was achieved at an abrasive concentration of 7%. The underlying reasons for this observation are clarified through the simulation results presented in this study. As shown in Fig. 11, although the initial abrasive concentration in the model is set at 6%, which is relatively low. However, the abrasives tend to accumulate near the wall after entering the slot,

which results in a local abrasive concentration significantly higher than 6%, intensifying inter-particle collisions and consequently reducing the abrasives' effectiveness in impacting the wall surface. An appropriate increase in abrasive volume concentration can enhance the frequency of particle impacts on the rock surface. However, excessive concentration leads to frequent inter-particle collisions, which hinder effective energy transfer.

4.2. Optimization design of AWJ rock slotting

Based on the above analysis, the previous experimental results can be effectively interpreted, and valuable guidance can be provided for optimization design in the application of AWJ slotting for hard rocks: (1) As shown in Fig. 11, backflow is generated during AWJ rock slotting. In conventional AWJ rock perforation, such backflow may strike the jet gun body, potentially causing damage (Surjaatmadja et al., 2008). To mitigate this, wear-resistant baffles are typically installed around the nozzle, using materials such as

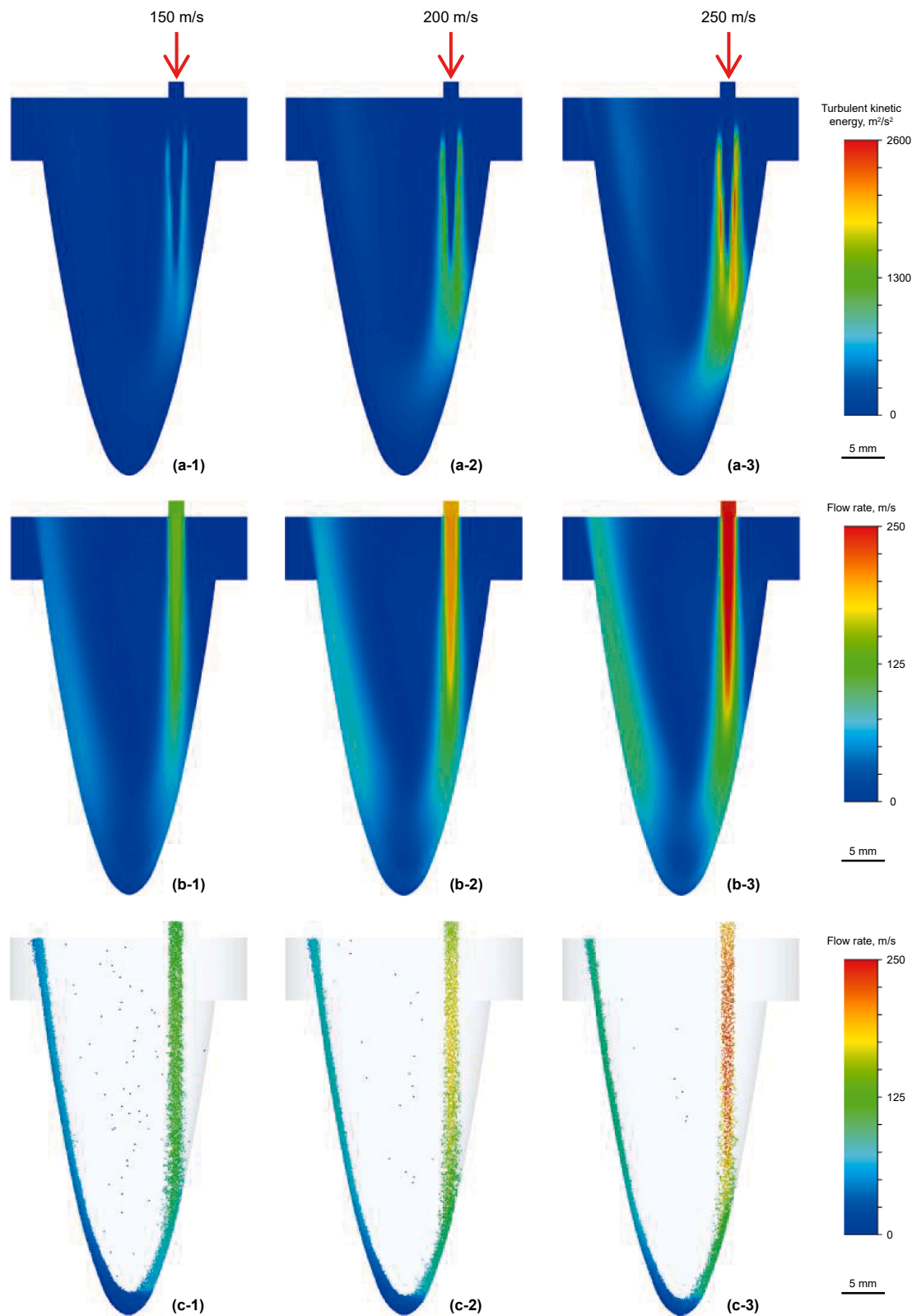


Fig. 17. Motion characteristics of abrasives and water at different jet velocities in Case 9, Case 3 and Case 10. (a-1, a-2, a-3) Contour plots of water turbulent kinetic energy, (b-1, b-2, b-3) contour plots of water flow rate, (c-1, c-2, c-3) spatial distribution of abrasive velocity.

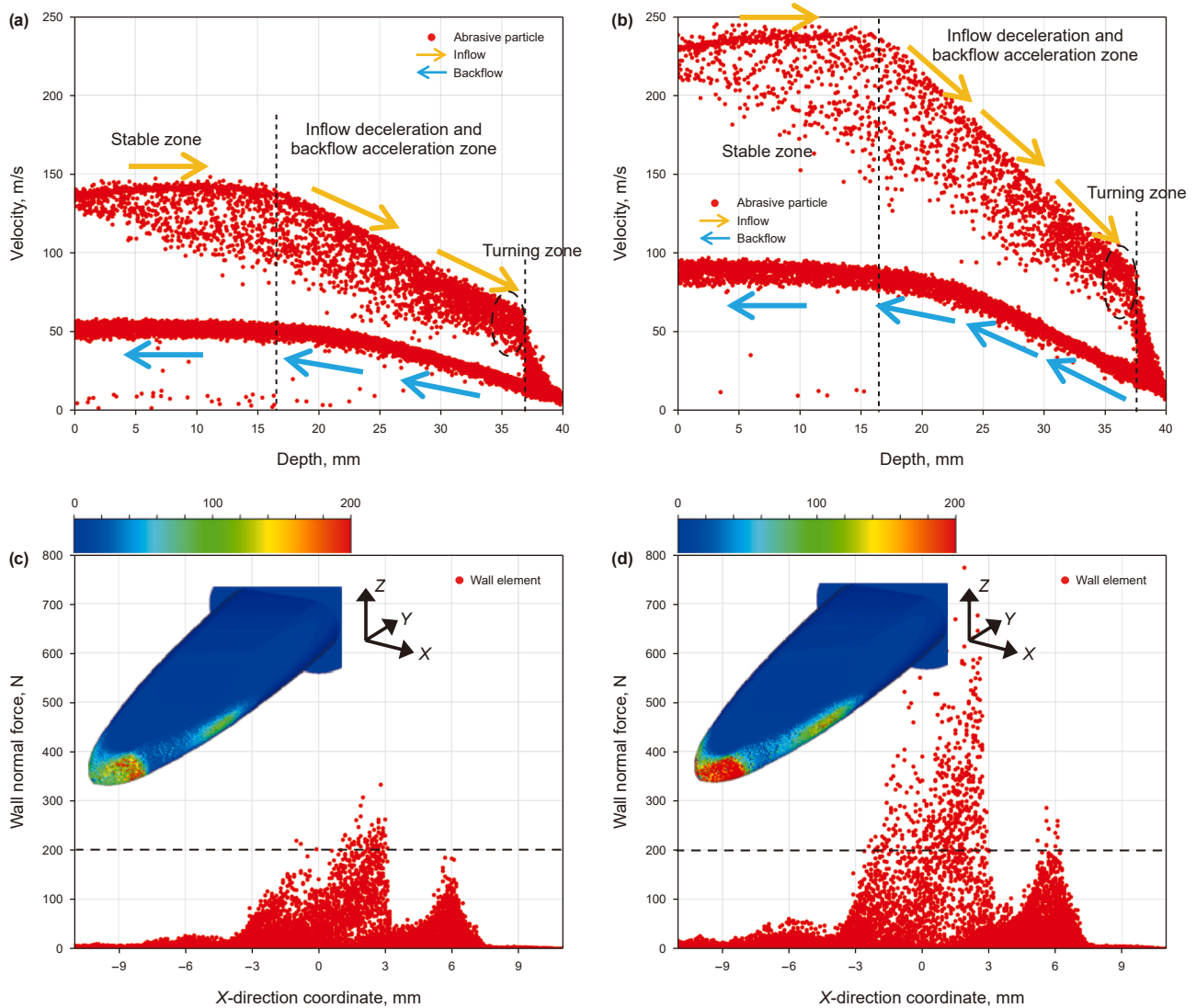


Fig. 18. Distribution of abrasive velocity and wall force in Case 9 with jet velocity of 150 m/s and Case 10 with jet velocity of 250 m/s. (a, b) Variation of abrasive velocity with depth, (c, d) distribution of wall normal force along the X-direction.

hard alloys or wear-resistant ceramics, which offer greater durability than stainless steel. During AWJ rock slotting, the increased slot length expands the backflow range, necessitating an enlarged protection area. It is recommended that the wear-resistant plate have a width 6 times the nozzle diameter and a length equal to the slot length plus 6 times the nozzle diameter. Based on the modeling approach proposed in this study, an AWJ rock slotting model incorporating the jet gun structure can be developed to investigate the backflow abrasive impact on the jet gun. (2) As shown in Fig. 14, the formation of a slot reduces turbulence and helps retain jet kinetic energy, thereby increasing the impact force on the wall. However, a longer slot is not always advantageous. In oil and gas well completion, deep axial penetration is often desired. Excessive nozzle movement disperses jet energy in the radial direction, diminishing its penetration capability. In addition, an excessively long slot may compromise the structural integrity of

the casing. As shown in Fig. 13, increasing the nozzle movement distance from 0 to 6 times the nozzle diameter significantly improves the flow field within the slot. However, further increasing the movement distance from 6 to 10 times yields only marginal improvements. Therefore, a nozzle movement distance equivalent to 10 times the nozzle diameter is sufficient. (3) Increasing jet velocity enhances the jet's kinetic energy and improves rock-breaking capability. However, higher jet velocity is not necessarily advantageous. As shown in Fig. 17, higher velocities also intensify turbulence, resulting in greater energy dissipation and a reduced energy utilization rate. Moreover, since jet acceleration is driven by the pressure difference across the nozzle, achieving higher jet velocities requires correspondingly higher pump pressure (Liu et al., 2023). Therefore, based on conventional AWJ rock perforation practices, a jet velocity of approximately 200 m/s is recommended for AWJ rock slotting.

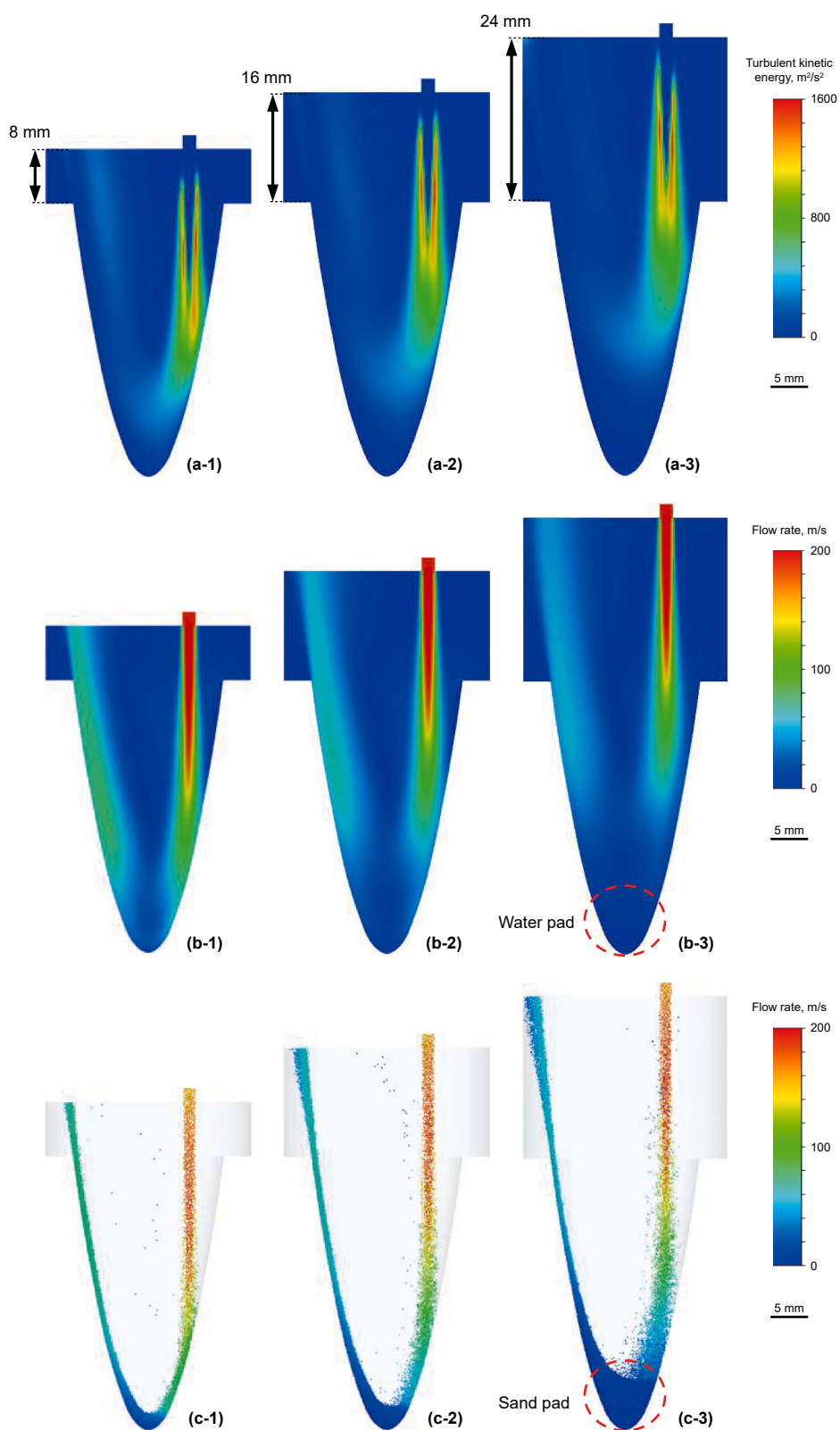


Fig. 19. Motion characteristics of abrasives and water at different jet distances in Case 3, Case 11 and Case 12. (a-1, a-2, a-3) Contour plots of water turbulent kinetic energy, (b-1, b-2, b-3) contour plots of water flow rate, (c-1, c-2, c-3) spatial distribution of abrasive velocity.

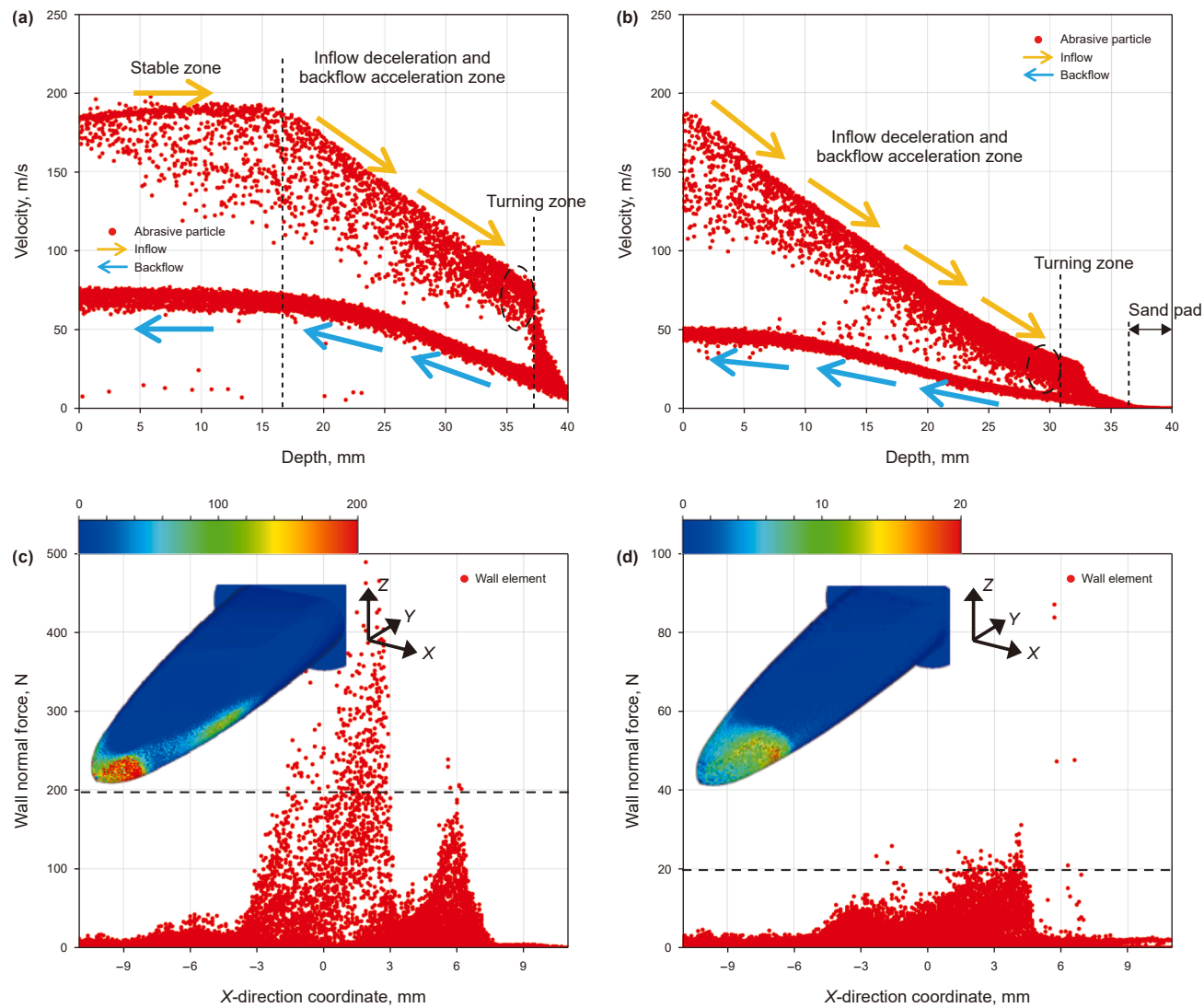


Fig. 20. Distribution of abrasive velocity and wall force in Case 3 with jet distance of 8 mm and Case 12 with jet distance of 24 mm. (a, b) Variation of abrasive velocity with depth, (c, d) distribution of wall normal force along the X-direction.

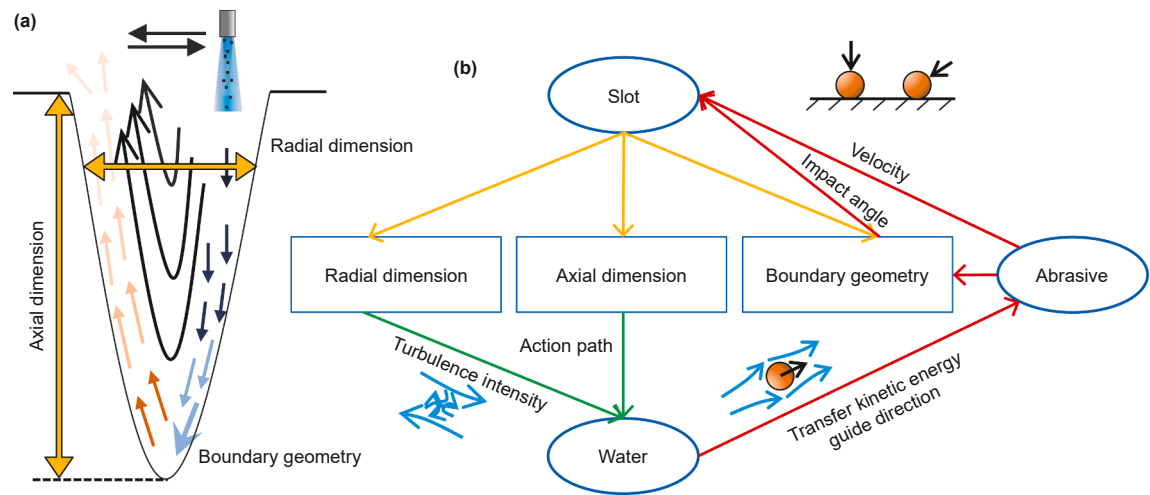


Fig. 21. Fluid-structure coupling mechanism in abrasive water jet rock slotting. (a) Schematic diagram of abrasive water jet rock slotting, (b) flowchart of the coupling mechanism among slot, water, and abrasive.

5. Conclusions

A numerical model of abrasive water jet (AWJ) rock slotting was developed using a coupled computational fluid dynamics-discrete element method (CFD-DEM) approach. The study investigated the effects of nozzle position, slot geometry, and jet parameters. By analyzing water turbulence, abrasive velocity distribution, and wall impact forces, the underlying mechanisms of AWJ slotting in hard rocks were elucidated. The main conclusions are as follows:

- (1) The essence of AWJ rock slotting lies in the coupled interaction among the slot, water, and abrasives. The shape of the slot influences water turbulence, which, in turn, affects abrasive acceleration. Continuous abrasive impacts lead to changes in the slot shape, with this cycle repeating over time, thereby driving the evolution of the slot.
- (2) The movement of abrasives within the slot primarily involves deceleration with the inflow, turning at the slot bottom, and acceleration along the sidewalls toward the annulus with the backflow. The velocity and impact angle of the abrasives determine the force exerted on the wall. The impact of abrasives on the slot bottom is significantly greater than that on the sidewalls.
- (3) AWJ slotting offers more efficient rock breaking and deeper perforation than conventional AWJ perforation by moving the nozzle to enlarge the slot cross-section, reduce turbulence, and preserve jet kinetic energy for rock removal. A nozzle moving range of approximately 10 times the nozzle diameter is recommended.

CRedit authorship contribution statement

Peng Xu: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mao Sheng:** Writing – review & editing, Supervision, Software, Resources, Project administration, Funding acquisition, Conceptualization. **Bo Zhang:** Writing – review & editing, Visualization, Validation, Supervision. **Shou-Ceng Tian:** Supervision, Resources, Project administration, Funding acquisition. **Zhong-Wei Huang:** Supervision, Project administration. **Gen-Sheng Li:** Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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