

Article

Pressure Response and Venting Mechanism of Entrapped Air Through Small Openings in a Drainage Pipeline

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Abstract

Rapid filling of urban drainage pipelines during intense rainfall can compress entrapped air and trigger pressure surges or geysering when air release through manhole-cover openings is restricted. Unlike studies focusing on simplified pipes or isolated shafts, this work examines the coupled air–water response of a prototype-scale drainage section with drop structures, branch inflows, variable-diameter inverted siphons, multiple shafts, and restricted manhole-cover venting. A three-dimensional unsteady air–water two-phase model was established and applied to nine two-stage inflow scenarios after validation against published rapid-filling pressure data. The results show that hydraulic slugs segmented the continuous crown air layer into localized air pockets and produced a high-pressure concentration zone upstream of the downstream diameter change, with a maximum shaft-top pressure of 29.2 kPa under the representative high-flow condition. In local shafts, insufficient venting through small openings, bottom water sealing, and continuous air supply jointly induced delayed geysering cycles characterized by pressure accumulation, breakthrough, relief, and re-accumulation, with a period of 110–120 s and peak pressures of 19–21 kPa. The second-stage rapid-filling flow rate dominated downstream peak pressures; when it increased from 9 to 11 m³/s, the peak pressure at a representative downstream shaft rose from 16 to 34 kPa. These findings clarify the mechanisms of high-pressure concentration and delayed geysering under restricted venting and support the identification of pressure-sensitive nodes in complex drainage networks.

Keywords: urban drainage pipeline; entrapped air; small-opening venting; pressure response; gas–liquid two-phase flow; CFD simulation



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1. Introduction

In recent years, extreme rainstorm events have occurred frequently. Urban drainage networks are subjected to large-volume rainwater inflows within short durations, causing the flow regime in pipes to shift rapidly from partially filled flow to high-fullness or even surcharged flow. During the rapid filling process, the gas phase space, originally distributed continuously at the pipe crown, is intercepted and compressed by the advancing water flow, leading to the formation of entrapped air pockets and localized high-pressure zones. When

compressed gas cannot be vented in a timely manner, violent transient pressure fluctuations are generated within the pipe network. These fluctuations may be released toward the ground surface through vertical structures such as manholes, inducing risks such as air–water geysers, manhole cover jumping, and even displacement. Such phenomena not only compromise the operational safety of the drainage system but also pose a threat to surface traffic and personnel safety. Therefore, revealing the mechanisms of air–water transient evolution and pressure response in drainage pipes under intense rainfall and rapid filling conditions is of significant engineering importance.

The air–water interaction during the rapid filling of pipelines has received considerable attention, with relevant research primarily focusing on localized mechanisms such as entrapped air pressurization, venting transients, shaft geysering, and manhole cover displacement. Starting from the formation mechanisms and experimental phenomena of shaft geysering, Leon [1,2] identified that the pressure gradient within the shaft, the upsurge of air–water mixtures, and the gas release process are critical factors inducing strong geysers. Regarding the venting process of entrapped air in pipelines, Zhou et al. [3] investigated rapid air expulsion through an orifice in a vertical water pipe, while Apollonio et al. [4] analyzed hydraulic transients induced by air expulsion during the rapid filling of undulating pipelines. These studies showed that the venting path and air-release intensity are closely associated with pressure fluctuations during rapid filling. For localized complex structures in urban drainage networks, Fang et al. [5] employed 3D CFD simulations to study air–water interactions in T-junction pipes, demonstrating that branch inflows alter localized gas entrapment and pressure distribution. Meanwhile, Wang and Vasconcelos [6,7] investigated the risk of manhole cover uplift caused by entrapped air release and air pressurization within shafts during rapid filling from the perspective of manhole cover displacement. Tijsseling et al. [8] discussed the kinetic response of ventilated manhole covers under air pressure using a non-linear spring-mass model. Qian et al. [9] further evaluated mitigation measures for shaft geysering in storm systems by combining experiments with numerical simulations. These studies provided a solid foundation for understanding localized gas entrapment, geysering, and manhole cover responses during rapid filling. However, their subjects were mostly limited to single pipe segments, individual shafts, or localized structures. Systematic discussions on the full-line air–water interaction and restricted venting through small openings in complex drainage sections—incorporating drop structures, branch inflows, variable-diameter inverted siphons, and multi-shaft nodes—remain insufficient.

Although the aforementioned studies effectively revealed localized mechanisms such as entrapped air pressurization, flow rate, and shaft geysering, actual urban drainage networks are characterized by long pipelines, numerous nodes, and complex boundaries. Engineering analysis requires the prediction of water advancement, gas transport, and pressure wave propagation at a full-line scale. Therefore, one-dimensional (1D) and quasi-1D air–water transient models remain essential tools for engineering-scale simulations. Vasconcelos et al. [10] proposed the Two-Component Pressure Approach (TPA) to describe the transition between free-surface and pressurized flows in drainage pipes, which was further extended to stormwater pipe systems by Sanders and Bradford [11]. León et al. [12] established boundary conditions suitable for free-surface, pressurized, and mixed flows specifically for nodes and drop shafts, while Bouso et al. [13] systematically summarized the development and limitations of mixed-flow models in stormwater systems. Subsequently, Cataño-Lopera et al. [14] applied mixed-flow models to the analysis of transient events in large-scale deep tunnel systems, and Li et al. [15] developed a coupled 1D-2D drainage network model, further enhancing engineering-scale simulation capabilities. In addition to traditional mixed-flow models, Demay and Hérard [16] and Re and Abgrall [17]

expanded the description methods for transient two-phase flow in pipes from the perspectives of compressible gas–liquid flow and BN-type non-equilibrium models, respectively. Yang et al. [18] combined SPH with the Preissmann slot method for the simulation of transient mixed flow in pipes. Simultaneously, commercial multiphase flow models, represented by OLGA, have also been employed for the calculation of slug flow and transient multiphase flow in long-distance pipelines [19,20]. Generally, the aforementioned models are suitable for full-line transport, pressure wave propagation, and rapid calculation across multiple scenarios. However, most still rely on cross-sectional average assumptions, empirical closure relations, or simplified node boundaries. They struggle to resolve 3D interface deformation, water seal formation, and localized restricted venting processes near drop shafts, branch inflows, variable-diameter inverted siphons, and manhole cover openings. Therefore, when the research focus shifts from full-line hydraulic transport to localized pressure-induced disaster mechanisms, 3D numerical models are required to provide supplementary analysis of the air–water interaction at critical nodes.

In summary, existing studies have investigated rapid filling mainly from two perspectives: localized three-dimensional air–water mechanisms and one-dimensional full-line transient transport. However, a scale gap remains between these two types of studies. Localized studies can reveal air pocket compression, geysering, and manhole-cover responses, but they generally focus on simplified pipes, isolated shafts, or individual structures and cannot fully describe pressure redistribution under multi-node interactions. One-dimensional models are suitable for full-line engineering analysis, but they rely on cross-sectionally averaged assumptions and simplified node boundaries, making it difficult to resolve three-dimensional interface deformation, water seal formation, restricted venting through small cover openings, and repeated gas–liquid interface oscillations within shafts. To address this gap, this study establishes a three-dimensional unsteady air–water two-phase model for a prototype-scale urban drainage pipe section incorporating drop structures, branch inflows, a downstream variable-diameter inverted siphon, multiple shafts, and restricted manhole-cover openings. The main contribution of this study is to clarify how rapid filling redistributes entrapped air and pressure in a complex drainage section with restricted venting, and to distinguish two pressure-response mechanisms: high-pressure concentration upstream of the downstream diameter reduction and delayed periodic geysering induced by localized water sealing, continuous air supply, and insufficient opening-mediated venting. The results provide support for identifying high-pressure-sensitive nodes, evaluating venting capacity, and improving anti-geysering design in complex urban drainage networks.

2. Numerical Model and Simulation Setup

2.1. Typical Pipe Section and Mesh Generation

A typical urban drainage pipeline was selected as the research object in this study. Figure 1 illustrates the model domain, which incorporates the main pipe, vertical shafts, branch inflows, drop structures, variable-diameter sections, and inverted siphons. This model was utilized to investigate the processes of compression, migration, and restricted venting of entrapped air through small manhole cover openings as the large-section drainage pipe transitions from partially filled to nearly full or surcharged states under intense rainfall conditions.

Figure 1a presents the schematic diagram of the model. For clarity of presentation, the pipe lengths between adjacent manholes were compressed in the figure; however, the annotated distances represent the actual spacing. Nine shaft nodes were established along the pipeline and numbered S-1# to S-9# in the downstream direction. These manholes were modeled according to current design specifications [21]. Based on their functions and the

flow direction, they were classified as follows: a drop structure (D-1#), ordinary manholes (O-1#–O-3#), four-way manholes (F-1#–F-2#), and downstream variable-diameter manholes (R-1#–R-2#). Specifically, D-1# was employed to characterize the aeration process of the upstream drop; F-1# and F-2# were used to represent the disturbance of branch inflows on the air–water movement in the main pipe; R-1# and R-2# were located at the inverted siphon section to characterize the effects of sudden diameter changes and downstream water seals on gas entrapment and pressure accumulation.

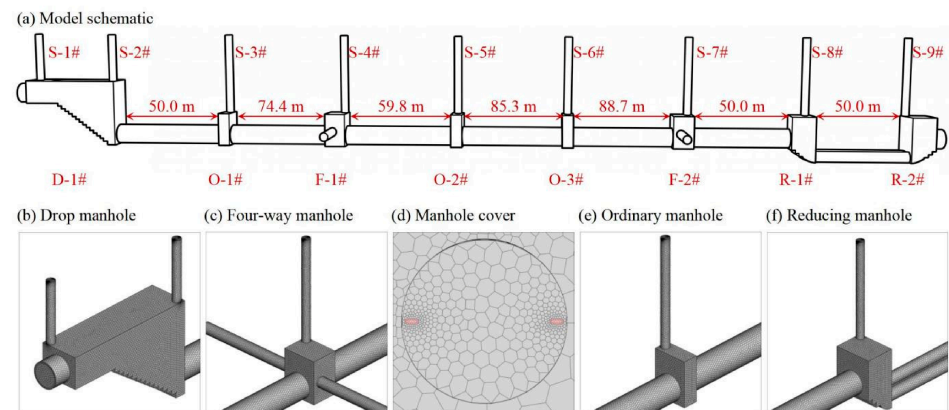


Figure 1. Schematic diagram and computational mesh of the typical drainage-pipe model.

The diameter of the main pipe was 2.4 m, and the overall slope was set to 0.0001. The depth of the ordinary manholes was 10 m, while the cover elevations of the other shafts were maintained at the same level. The four-way manholes incorporated two lateral branch pipes with diameters of 1.05 m. In the downstream variable-diameter section, the main pipe transitioned into two pipes with diameters of 1.2 m; this inverted siphon structure was designed to facilitate crossing an expressway. Additionally, the manhole covers were circular structures with a diameter of 0.7 m. Each cover was equipped with two small openings, with the venting area of a single opening being 3 cm².

Figure 1b–f display the local mesh partitioning for the drop manhole, four-way manhole, manhole-cover openings, ordinary manhole, and reducing manhole, respectively. To improve the resolution of velocity gradients and shear stresses near the solid walls of the main pipe, branch pipes, shafts, and diameter-transition sections, boundary-layer meshes were generated near these main solid boundaries. Five boundary layers were used with a growth rate of 1.2. The local mesh scale near the manhole-cover openings was set to 0.001 m, while the mesh scales near the shaft throats, branch junctions, and diameter-transition exits were set to 0.05 m.

Considering that air–water interface advancement, segmentation of the continuous crown air phase, and localized air-pocket compression during rapid filling mainly occur in the main pipe, the regular mesh scale of the main pipe directly affects the calculation of the overall air–water motion and pressure field. Therefore, mesh-independence analysis was conducted for five main-pipe mesh scales: 0.30 m, 0.25 m, 0.20 m, 0.15 m, and 0.10 m. The meshes were generated using Fluent Meshing, and the overall mesh quality was maintained at approximately 0.5. The steady open-channel condition before rapid filling was selected as the test case, with the main-pipe inlet flow rate set to 1.0 m³/s and the branch inlets closed. The steady pressure at manhole O-2# was selected as the monitoring indicator to characterize the sensitivity of the stable pressure field in the computational domain to the main-pipe mesh scale under the baseline open-channel condition.

As shown in Table 1, when the main-pipe mesh scale was refined from 0.30 m to 0.20 m, the steady pressure at O-2# gradually approached the fine-mesh result. When the

mesh scale was further refined from 0.20 m to 0.15 m and 0.10 m, the pressure variation became small. The pressure difference between the 0.20 m mesh and the finest 0.10 m mesh was approximately 0.02 kPa, corresponding to a relative difference of approximately 0.19%. Therefore, considering both computational accuracy and the computational cost of prototype-scale unsteady air–water two-phase simulations, the main-pipe mesh scale of 0.20 m was finally selected for the subsequent rapid-filling simulations.

Table 1. Mesh-independence analysis under the steady open-channel condition.

Mesh Case	Manhole-Cover Opening Mesh Scale (m)	Shaft Throat, Branch Junction, and Diameter-Transition Mesh Scale (m)	Main-Pipe Mesh Scale (m)	Steady Pressure at O-2# (kPa)	Relative Difference from Finest Mesh (%)
M1	0.001	0.05	0.30	11.02	6.58
M2	0.001	0.05	0.25	10.43	0.87
M3	0.001	0.05	0.20	10.36	0.19
M4	0.001	0.05	0.15	10.37	0.29
M5	0.001	0.05	0.10	10.34	0.00

2.2. Governing Equations and Solution Methods

To characterize the air–water interface evolution, entrapped-air compression, and air expulsion through small manhole-cover openings during the rapid filling of a typical drainage pipeline, a three-dimensional unsteady air–water two-phase flow model was established. The water phase was treated as an incompressible fluid, while the gas phase was modeled as a compressible ideal gas. The model solved the conservation equations of mass, momentum, and energy, which are expressed as follows:

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

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

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot [\mathbf{u}(\rho E + p)] = \nabla \cdot (k_{eff} \nabla T) + \nabla \cdot (\mathbf{u} \cdot \tau_{eff}) + S_h \quad (3)$$

where ρ is the fluid density; t is time; $\mathbf{u}$ is the velocity vector; p is the pressure; τ is the viscous stress tensor; g is the gravitational acceleration; E is the total energy; T is the temperature; k_{eff} is the effective thermal conductivity; τ_{eff} is the effective stress tensor; and S_h is the heat source term.

The air–water interface was captured using the Volume of Fluid (VOF) method [22]. In the VOF framework, the water and gas phases share a single velocity field, and the interface position is represented by the phase volume fractions. In the absence of phase change and interphase mass transfer, the phase volume-fraction transport equation can be written as

$$\frac{\partial (\alpha_q \rho_q)}{\partial t} + \nabla \cdot (\alpha_q \rho_q \mathbf{u}) = 0 \quad (4)$$

where α_q and ρ_q are the volume fraction and density of phase q , respectively. The subscripts w and g denote the water and gas phases, respectively. The phase volume fractions satisfy

$$\alpha_w + \alpha_g = 1 \quad (5)$$

The cell-averaged mixture density and viscosity used in the governing equations were determined by volume-fraction weighting:

$$\rho = \alpha_w \rho_w + \alpha_g \rho_g, \quad \mu = \alpha_w \mu_w + \alpha_g \mu_g \quad (6)$$

In the numerical implementation, the volume-fraction equation of one phase was solved, and the volume fraction of the other phase was obtained from Equation (5). The volume-fraction equation was discretized using the Compressive Scheme to mitigate numerical diffusion during interface transport, thereby maintaining a sharper representation of the crown air layer, local water seals, and gas–liquid interface oscillations within the shafts. It should be noted that the Compressive Scheme was used to reduce, rather than eliminate, numerical diffusion at the air–water interface.

Because the gas phase was treated as a compressible ideal gas, the energy equation was solved to maintain thermodynamic consistency among pressure, density, and temperature during gas compression and expansion. The gas density was updated using the ideal gas equation of state, whereas the water density was assumed to be constant. The present study focuses on the pressure response induced by entrapped-air compression, restricted venting through small manhole-cover openings, and delayed geysering caused by water sealing, rather than on the temperature field itself. Therefore, temperature distributions are not discussed separately in the following analysis. The thermal response associated with gas compression and expansion was included through the energy equation and the ideal gas equation of state; however, under the present conditions, the periodic pressure response at manhole O-1# was mainly governed by the formation and reconstruction of the bottom water seal, continuous air supply from the main pipe, and the venting capacity of the small manhole-cover openings.

The incompressibility assumption for the water phase can be justified by the pressure scale involved in this study. The typical peak pressures obtained in the simulations were on the order of several tens of kPa in gauge pressure. Taking 34 kPa as a representative pressure increment and using a water bulk modulus of approximately 2.2×10^9 Pa, the relative density variation of water can be estimated as

$$\frac{\Delta \rho_w}{\rho_w} \approx \frac{\Delta p}{K_w} \approx \frac{34 \times 10^3}{2.2 \times 10^9} \approx 1.5 \times 10^{-5} \quad (7)$$

This magnitude is much smaller than the effects of air–water interface advancement, entrapped-air compression, and local water-seal formation on the pressure response. Therefore, neglecting water compressibility is reasonable under the present simulation conditions.

The RNG k - ϵ turbulence model was adopted, together with wall functions for near-wall treatment. This choice was mainly based on the requirements of prototype-scale, multi-scenario, unsteady simulations for a complex drainage pipe section. Fang et al. [5] conducted three-dimensional CFD simulations of air–water interaction in stormwater T-junction pipes and compared several RANS turbulence models, including the standard k - ϵ , RNG k - ϵ , realizable k - ϵ , standard k - ω , and SST k - ω models. Their results showed that the RNG k - ϵ and SST k - ω models performed better than the other RANS models in reproducing transient pressure oscillations and geyser-related processes. Considering that the present study focuses on prototype-scale water advancement, entrapped-air compression, pressure redistribution, and restricted opening-mediated venting, the RNG k - ϵ model provides a practical balance among numerical robustness, computational cost, and engineering-scale applicability. It should be noted that this model is not intended to fully resolve small-scale anisotropic turbulence near branch junctions, drop structures, shaft interiors, or manhole-cover openings.

Numerical simulations were performed using ANSYS Fluent 2025 R2. The governing equations were discretized using the finite volume method, and a pressure-based transient solver was adopted. The PISO algorithm was used for pressure–velocity coupling [23] to satisfy the coupling among the pressure field, velocity field, and continuity constraint during the transient air–water process. A second-order implicit scheme was adopted for

temporal discretization. For spatial discretization, the momentum, energy, and turbulence equations were discretized using the second-order upwind scheme, whereas the VOF volume-fraction equation was discretized using the Compressive Scheme. Within each time step, the scaled residuals of the continuity equation, the three momentum equations, the k , ϵ , and energy equations were required to decrease below 10^{-6} . Adaptive time stepping was adopted according to the Courant-number constraint, with the time-step size varying from 10^{-5} s to 10^{-4} s. The total simulated duration of different cases ranged from 500 s to 1000 s, which was sufficient to capture the early-stage air–water transient response induced by rapid filling and the subsequent localized delayed geysering process.

No-slip boundary conditions were applied to the walls. Based on previous project experience, the equivalent wall roughness height of the drainage pipe was set to 0.005 m to represent the rough inner-wall condition of aged drainage pipelines in practical engineering. Open Channel boundary conditions were applied at the main-pipe inlet, downstream outlet, and branch-pipe inlets to represent the stratified air–water flow state at these boundaries. The small manhole-cover openings were designated as pressure outlet boundaries to simulate free air intake and expulsion when the openings communicate with the atmosphere. Unless otherwise specified, all pressure results reported in the following sections are gauge pressures.

2.3. Simulation Scenarios and Validation

Simulation boundaries were established using a two-stage approach consisting of steady-state operation (Stage I) and rapid filling (Stage II). Stage I was used to establish the baseline open-channel drainage condition before rainfall, during which the main pipe maintained a relatively low filling ratio and a continuous gas phase at the pipe crown. The Stage-I flow rates were determined according to the surveyed operating range of the investigated drainage pipe and were used to construct low, normal, and high initial water-level conditions. For each Stage-I condition, the corresponding water depth and velocity field were obtained from the steady open-channel solution constrained by the pipe geometry, slope, wall roughness, and inlet flow rate, rather than being prescribed independently. Stage II was used to represent the high-load state following a rapid increase in inflow under intense rainfall, where the filling ratio rose rapidly and localized air pockets were compressed by the advancing water flow. The flow rates for Stage I were set at 0.5, 1.0, and $1.5 \text{ m}^3/\text{s}$, representing low, normal, and high initial water-level conditions, respectively. The flow rates for Stage II were set at 9.0, 10.0, and $11.0 \text{ m}^3/\text{s}$, representing high-filling-ratio open-channel flow, near-full transitional flow, and full-pipe limiting flow, respectively. Consequently, nine simulation scenarios were established, as shown in Table 2.

Table 2. Simulation scenarios.

Case	Stage-I Flow Rate (m^3/s)	Stage-II Flow Rate (m^3/s)	Hydraulic Condition
SY-1	0.5	9	Low initial water level–high-filling open-channel flow
SY-2	0.5	10	Low initial water level–near-full transitional flow
SY-3	0.5	11	Low initial water level–full-pipe limiting flow
SY-4	1	9	Normal initial water level–high-filling open-channel flow
SY-5	1	10	Normal initial water level–near-full transitional flow
SY-6	1	11	Normal initial water level–full-pipe limiting flow
SY-7	1.5	9	High initial water level–high-filling open-channel flow
SY-8	1.5	10	High initial water level–near-full transitional flow
SY-9	1.5	11	High initial water level–full-pipe limiting flow

For model validation, the experimental and numerical investigation conducted by Liu et al. [24] on various filling patterns in inverted siphon pipelines was selected as a benchmark. This benchmark was chosen because its dominant pressure-generation mechanism

is closely related to the main process considered in the present study. In both cases, rapid inflow interacts with an initially stratified or trapped gas phase, while downstream hydraulic constraints or water-seal effects restrict continuous air release, leading to air-pocket compression, slug formation, transient pressure fluctuation, and subsequent pressure recession. These processes are directly relevant to the pressure accumulation upstream of the downstream inverted siphon and the entrapped-air pressurization mechanism analyzed in this study. Although the present model further includes multiple shafts, branch inflows, drop structures, and small manhole-cover openings, the early-stage high-pressure response is mainly governed by main-pipe rapid filling, hydraulic blockage or water sealing near the downstream inverted siphon, and entrapped-air compression. The small cover openings provide limited venting capacity during the early rapid-filling stage and mainly influence the subsequent local pressure relief and water-level rise within shafts after a distinct water column has formed.

Figure 2 presents the model validation results based on the rapid filling case from Liu et al. [24]. It should be noted that PT-1#, PT-5#, and PT-8# denote the pressure measurement points from the cited literature and do not represent the monitoring points within the typical drainage pipeline model used in this study. Overall, the numerical results successfully reproduced the primary trends of the experimental pressure fluctuations. Specifically, the maintenance of high pressure, the rapid decline, and the subsequent stabilization observed at PT-1# showed good agreement with the experimental data, while the pressure levels and variation trends at PT-5# and PT-8# also remained largely within the range of experimental observations. The Nash–Sutcliffe efficiency (NSE) values for PT-1#, PT-5#, and PT-8# were 0.951, 0.871, and 0.854, respectively, indicating that the numerical method effectively captured the key features of the process, such as air–water interface advancement, entrapped air pressurization, and pressure redistribution. Although minor deviations persisted in local high-frequency fluctuations and peak magnitudes, the overall error remained within an acceptable range. This demonstrates that the three-dimensional compressible air–water two-phase solver adopted in this study can reproduce the fundamental rapid-filling air–water processes, including interface advancement, entrapped-air pressurization, slug-related pressure redistribution, and pressure recession. Therefore, it is suitable for the subsequent mechanism analysis of rapid filling, pressure accumulation, and restricted venting in the typical drainage pipeline considered in this study.

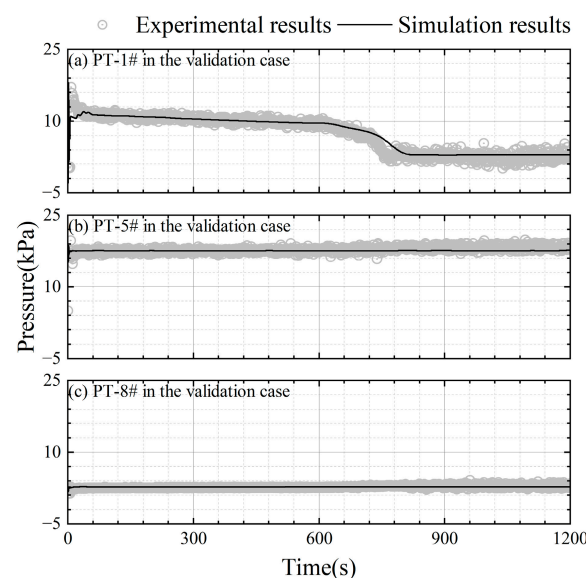


Figure 2. Verification of the numerical model under rapid filling. (a) PT-1# in the validation case; (b) PT-5# in the validation case; and (c) PT-8# in the validation case.

3. Results and Discussion

3.1. Linkage Process of Global Pipeline Intense Air Pressurization

To investigate the air–water transient mechanism under rapid filling conditions in stormwater pipelines, Scenario SY-3—characterized by a rapid transition from a low initial water level to the maximum surge flow rate—was selected as a representative case to analyze the global compression, fragmentation, and release processes of entrapped air. Representative moments for the six stages of this scenario are presented in Figure 3 to reflect the evolution of air–water movement across the entire pipeline during the rapid filling process.

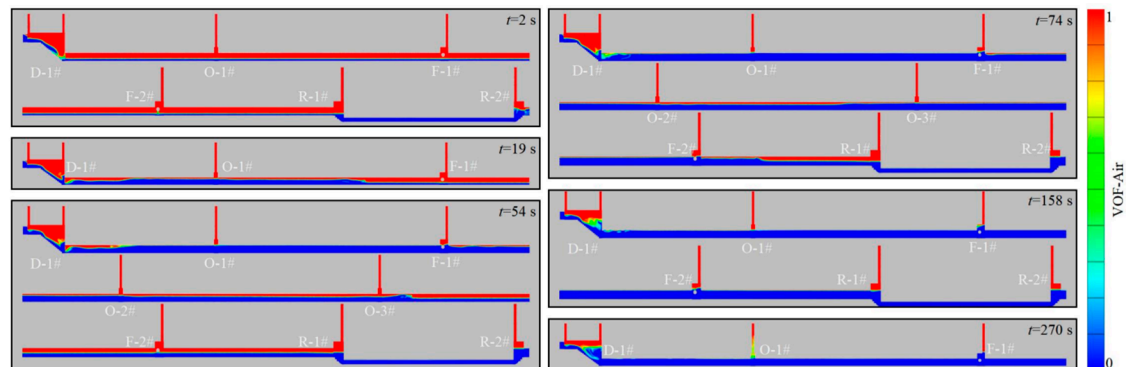


Figure 3. Representative moments of the global air–water evolution.

The system was in the high-pressure triggering stage during 0–30 s. For instance, the main pipe maintained a relatively continuous stratified flow at 2 s, and the gas phase space at the pipe crown had not yet been significantly fragmented; however, blowout had already occurred at the downstream reduced-diameter section and manhole R-2#, indicating that the intense air pressurization process was initially triggered by downstream boundary constraints. The system entered the first slug formation stage between 30 and 50 s. Specifically, after the flow advanced to the vicinity of the central four-way manhole at 19 s, a momentum exchange occurred between the main pipe inflow and the branch pipe inflow between O-1# and F-1#, forming the first hydraulic slug that began to locally obstruct the previously continuous gas phase. The system transitioned into the second slug formation stage during 50–70 s. A second hydraulic slug was formed near O-3# and F-2#, causing air pockets near O-2# and O-3# to be entrapped between the two slugs, which significantly enhanced local gas compression. Consequently, the air–water state within the pipeline gradually transitioned from global connectivity to the coexistence of multiple localized air pockets. The system entered the chain outbreak stage between 70 and 100 s. The second slug continued to advance downstream and merged with the branch pipe inflow near F-2#, exerting intense compression on the downstream air pocket. At this stage, the region upstream of the diameter reduction became the core response zone for the intense air pressurization. The system entered the release and recession stage during 100–400 s. By 158 s, a multi-slug flow pattern had formed in the main pipe, making it difficult for gas to be transported continuously along the pipeline. Pressure in the mid-to-downstream regions gradually receded; however, the slug between O-1# and F-1# persisted, while the upstream drop structures continued to entrain air. Finally, between 200 and 400 s, the upstream region of the pipeline further developed into a delayed geyser stage. While the downstream response had weakened significantly, the drop structures continued to entrain air, where small bubbles merged into larger air pockets within the main pipe and were transported into O-1#. Due to the formation of a water seal at the bottom of manhole

O-1#, gas could not be discharged in a timely manner, eventually inducing a delayed air–liquid surge.

To further explore how the aforementioned air–water evolution process transforms into pressure fluctuations at the manhole covers, the pressure fluctuation variations at the top of each shaft along the pipeline are plotted in Figure 4. Specifically, Figure 4a displays the pressure variations throughout the entire process from 0 to 400 s, while Figure 4b provides a localized magnification of the rapid triggering and chain outbreak stages from 0 to 100 s.

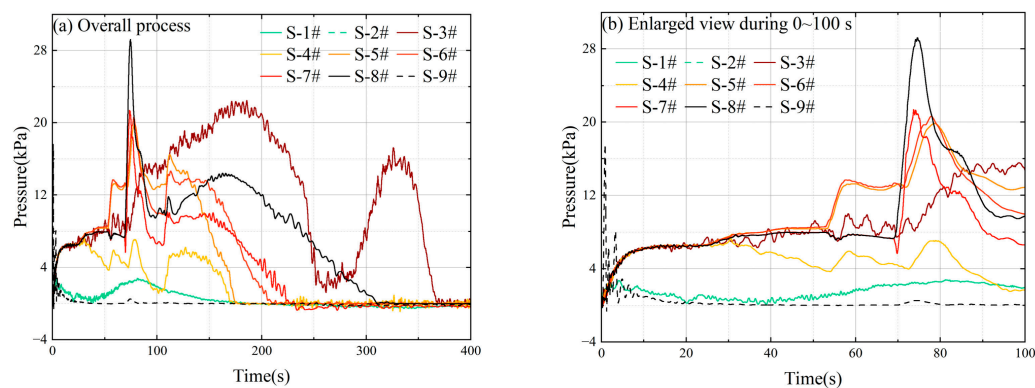


Figure 4. Pressure responses at manhole tops under scenario SY-3. (a) Overall process; and (b) Enlarged view during 0~100 s.

A short-term pressure spike exceeding 15 kPa was first observed in shaft S-9# during the high-pressure triggering stage (0–30 s); subsequently, the pressures in the mid-to-downstream shafts rose synchronously to approximately 6–8 kPa. This indicated that no significant hydraulic obstruction had formed within the main pipe and the gas phase space at the pipe crown remained in a state of global compression as a large-scale continuous air pocket. Upon entering the slug formation stage (30–70 s), the pressures along the pipeline began to differentiate significantly as the first and second hydraulic slugs were formed. For instance, the pressure near S-4# was found to decline, while the pressures in the mid-to-downstream shafts, such as S-5#, S-6#, S-7#, and S-8#, continued to rise. This suggests that localized air pockets began to undergo independent compression after being fragmented by the slugs.

During the chain outbreak stage (70–100 s), the pressure in S-8# rose rapidly to the maximum value of the entire process, with a peak of approximately 29 kPa. High-pressure peaks subsequently appeared in S-7#, S-6#, and S-5#, with the peaks of S-6# and S-7# both exceeding 20 kPa. It was revealed that after the air pocket upstream of the downstream diameter reduction underwent extreme compression, the high-pressure disturbances were not confined to the downstream region but further propagated backward toward the midstream. Furthermore, a maximum pressure of 29.2 kPa was reached in S-8# at $t = 74.6$ s, which induced a reverse pressure response in S-5# and S-6#.

After 100 s, the pressures in the mid-to-downstream shafts generally entered the release and recession stage, although distinct spatial differences were observed in the depressurization process of each shaft. The pressure in S-4# approached zero after approximately 170 s, whereas the release in S-8# was delayed until approximately 330 s, demonstrating that the gas flow rate pathways were discontinuous under the coexistence of multiple slugs. In contrast, a high pressure of approximately 18–22 kPa was maintained in S-3# during 120–200 s. Although the pressure subsequently declined, it rose again to approximately 16 kPa near 300–340 s, corresponding to the delayed geyser stage described previously. These results indicate that the continuous air entrainment from the upstream drop struc-

tures, combined with the local water seal between O-1# and F-1#, allowed localized air pockets to re-accumulate and be released even after the primary outbreak process had concluded.

3.2. Localized Manhole Opening Venting and Delayed Geysering Mechanism

The previous section analyzed the global air–water linkage during rapid filling at the pipeline-wide scale. However, opening-mediated venting and delayed geysering predominantly occurred within localized shafts. Their formation was influenced not only by pressure transmission within the main pipe but also by the water seal at the shaft bottom, localized gas supply, the venting capacity of the manhole cover opening, and the repetitive rising and falling of the gas–liquid interface. Consequently, manhole O-1#, which exhibited a typical periodic response, was selected for localized analysis, and Scenario SY-5 was utilized to further discuss the delayed geysering mechanism under conditions of restricted opening venting.

Figure 5 presents representative moments of the localized air–water distribution in manhole O-1# under Scenario SY-5. At $t = 73.1$ s, gas phase accumulation and compression predominated at the shaft bottom, and water had not yet significantly entered the shaft column, indicating that the gas still maintained a relatively connected venting space. At $t = 206.2$ s, the gas within the shaft was further pressurized, and the gas phase space near the shaft bottom was compressed, corresponding to a prolonged pressure accumulation process. At $t = 247.2$ s, water began to intrude into the shaft bottom and formed a localized water seal, thereby restricting the external gas flow rate channel; consequently, the gas at the shaft bottom transitioned from a dischargeable state to a restricted compression state. At $t = 269.2$ s, the pressurized air pocket broke through the water seal, and the air–liquid mixture surged significantly upward along the shaft, entering the delayed geysering stage. At $t = 310.0$ s, a portion of the gas was released through the manhole cover opening, and the water in the shaft began to recede, although continuous air supply conditions persisted within the main pipe. At $t = 360.0$ s, the liquid level at the shaft bottom rose again, indicating the formation of a new water seal and geysering cycle.

The aforementioned air–water evolution demonstrates that the process within manhole O-1# was not a simple continuous venting event; rather, it involved a cycle of repetitive gas accumulation, water seal formation, air pocket breakthrough, opening-mediated venting, and subsequent resealing. While the opening provided a pressure relief pathway for the gas in the upper shaft column, the compressed air pocket at the bottom could not be fully released in a timely manner when the shaft bottom was blocked by a water seal and upstream air supply continued. Consequently, air re-accumulated after a certain interval and triggered a new surge.

Figure 6 further presents the pressure time histories at the bottom, middle, and top measurement points of manhole O-1#. Between 0 and 70 s, the three pressure curves rose basically in synchronization, with the pressure increasing from approximately 3 kPa to 17 kPa, indicating that the shaft interior was primarily dominated by the global compression of a connected air cavity. Subsequently, the pressure continued to oscillate and rise, reaching the first high-pressure peak of approximately 21 kPa at 206 s, which corresponded to the strong pressure accumulation state at $t = 206.2$ s shown in Figure 5.

After 206 s, the pressure entered a rapid recession stage. The decline was most pronounced at the top measurement point, which dropped to approximately 7 kPa near 260–270 s, while the bottom measurement point remained at approximately 13–15 kPa. This vertical pressure gradient demonstrated that the manhole cover opening exerted a significant pressure relief effect on the upper shaft column, whereas the shaft bottom remained governed by the localized water seal and gas supply from the main pipe. When

the time progressed to 269.2 s, the pressures at the three measurement points rose rapidly again to 19–20 kPa, corresponding to the delayed geysering process in Figure 5, where the air pocket broke through the water seal and surged upward along the shaft.

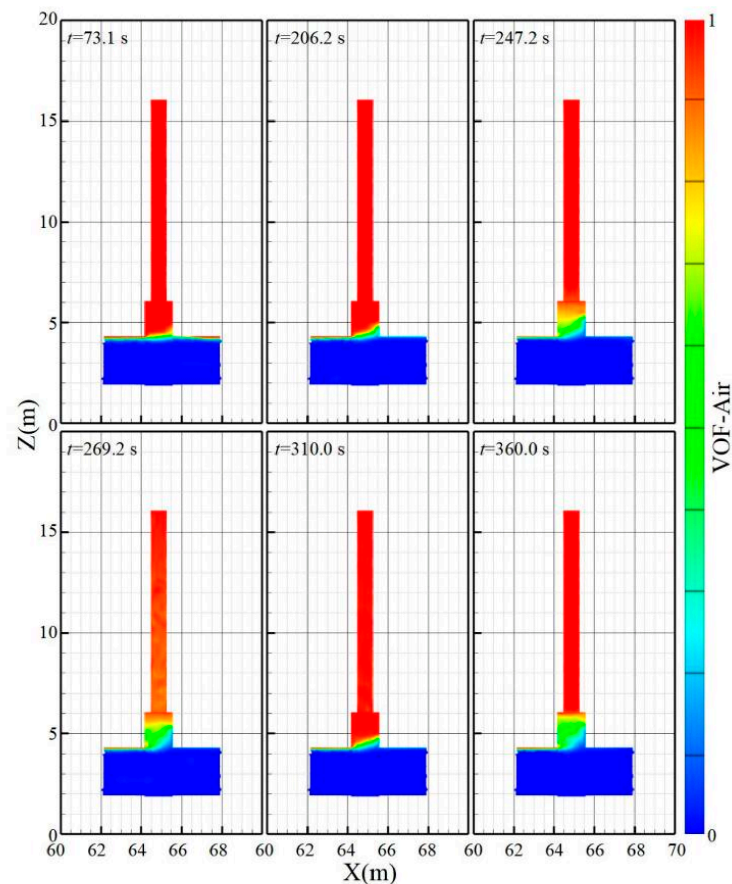


Figure 5. Local air–water evolution at O-1#.

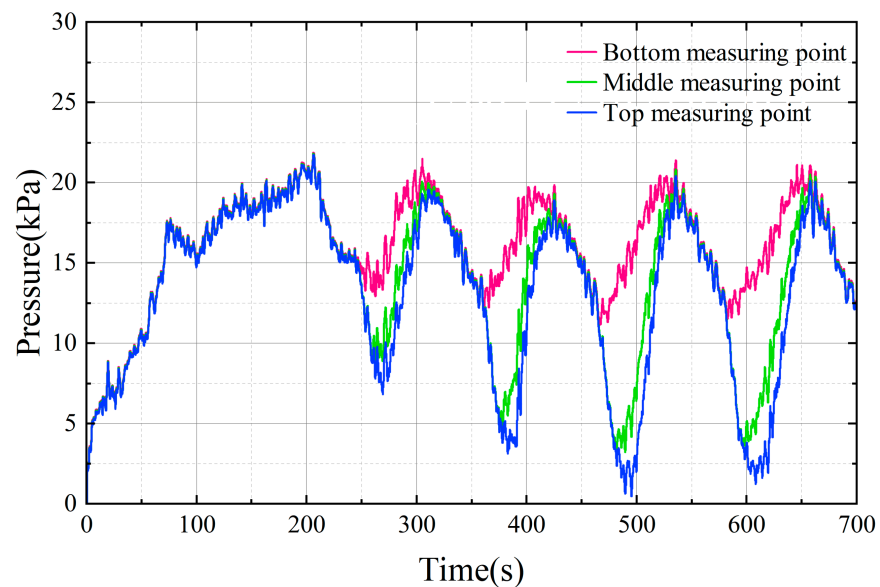


Figure 6. Pressure responses at the bottom, middle, and top measuring points of O-1#.

After 300 s, the pressure curves entered a repetitive cycle of pressure accumulation and pressure relief. Multiple peaks appeared near 310 s, 430 s, 540 s, and 660 s, most of which were maintained within the 19–21 kPa range, with an interval of approximately

110–120 s between adjacent peaks. Consequently, it was evident that although opening-mediated venting could reduce the pressure in the upper shaft column, manhole O-1# still exhibited periodic delayed geysering under the combined influence of continuous gas supply and localized water seals.

3.3. Pressure Response of Typical Measurement Points to Two-Stage Flow Rate Variations

As previously established, the peak pressures at the top of the shafts along the pipeline were primarily concentrated within the 0–100 s interval. This period corresponded to the high-pressure triggering, slug formation, and chain outbreak stages during the rapid filling process, representing the stage where differences in pressure response under various flow rate conditions were most pronounced. Consequently, the 0–100 s interval was selected as the primary analysis period. Furthermore, the top locations of S-3# and S-8# were selected as representative cases to discuss the effects of variations in Stage I and Stage II flow rates on the localized pressure time–history responses, respectively. Specifically, measurement point S-3# was utilized to characterize the localized pressure fluctuation process in the mid-upstream region, while measurement point S-8# corresponded to the high-pressure sensitive area experiencing higher peak pressures along the pipeline.

Figure 7 presents the pressure time–history variations at the top of S-3# within the 0–100 s interval. Scenarios SY-2, SY-5, and SY-8 were selected in Figure 7a to compare the pressure responses under conditions of identical Stage II flow rate but varying Stage I flow rates. A rapid pressure increase was observed in the initial stage for all three scenarios, but significant differences existed in their subsequent response processes. For Scenario SY-2, the pressure rose to approximately 5 kPa within the first 10 s, subsequently maintained within the 4–5 kPa range for an extended period, and did not exhibit another significant increase until after 80 s, reaching 10 kPa near 100 s. Scenario SY-5 exhibited a more intense initial pressurization, with multiple localized fluctuation peaks appearing between 10 and 30 s, oscillating within the 12–14 kPa range. The pressure was then maintained at the 10 kPa level from 40 to 70 s, before rising again to 15 kPa after 80 s. For Scenario SY-8, the initial pressure was lower than that of SY-5, but it continued to rise after 50 s, reaching approximately 17 kPa near 70–80 s, and subsequently stabilized at a relatively high level of 15–17 kPa overall. Variations in the Stage I flow rates were found to significantly alter the stage-specific characteristics of the pressure response at the top of S-3#. A higher Stage I flow rate did not generate the maximum pressure in the initial stage, but it elevated the pressure levels in the middle and later stages. Conversely, under a moderate Stage I flow rate, the initial localized fluctuations were more intense, indicating that the Stage I flow rate primarily exerted a nonlinear modulation effect on the subsequent pressure accumulation process by altering the initial water level and the state of the gas phase space.

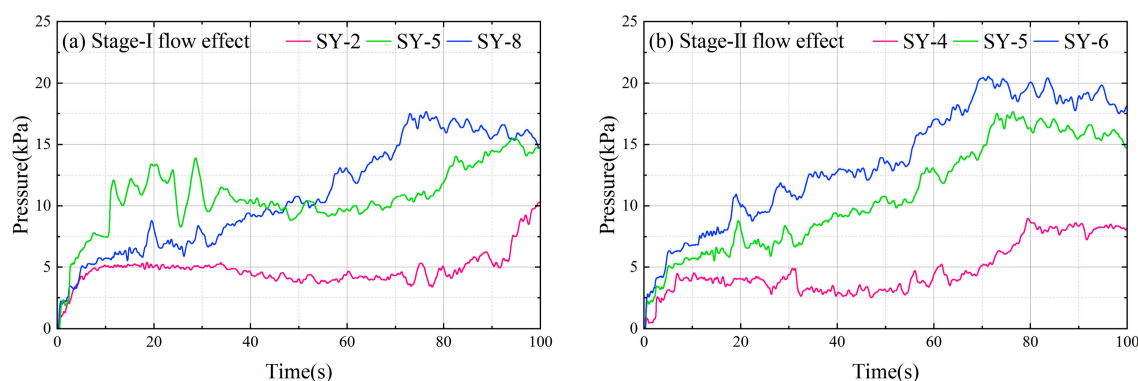


Figure 7. Temporal variation of pressure at the top of S-3# under two-stage flow-rate changes. (a) Stage-I flow effect; and (b) Stage-II flow effect.

Figure 7b further compares Scenarios SY-4, SY-5, and SY-6 to analyze the pressure responses under conditions of identical Stage I flow rate but varying Stage II flow rates. Scenario SY-4 exhibited the lowest overall pressure level, which was primarily maintained within the 3–5 kPa range from 0 to 60 s. Although an increase occurred after 80 s, the maximum value remained below 10 kPa. The pressure in Scenario SY-5 was significantly higher than that in SY-4 and continuously increased over time, exceeding 10 kPa after 50 s and reaching 17 kPa near 70–80 s. Scenario SY-6 demonstrated the highest pressure level, surpassing those of SY-4 and SY-5 overall. It further increased after 60 s and was maintained within 18–20 kPa during the 70–90 s period. These observations demonstrate that the rapid filling flow rate in Stage II exerted a more direct amplifying effect on the pressure at the top of S-3#. As the Stage II flow rate increased, the intensity of the water flow advancement was enhanced, resulting in more severe localized gas compression and an earlier transition of the high-pressure response into the elevated value range.

As indicated by Figure 4, the top location of measurement point S-8# represented the high-pressure sensitive region where the peak pressures across the entire pipeline were most concentrated. Furthermore, since the influence of Stage I flow rate variations on the pressure response at this location within the 0–100 s interval was relatively insignificant, the subsequent comparative analysis was conducted solely with respect to Stage II flow rate variations. Figure 8 presents the pressure time–history variations at the top of S-8# under different Stage II flow rate conditions while the Stage I flow rate was maintained at $1.0 \text{ m}^3/\text{s}$.

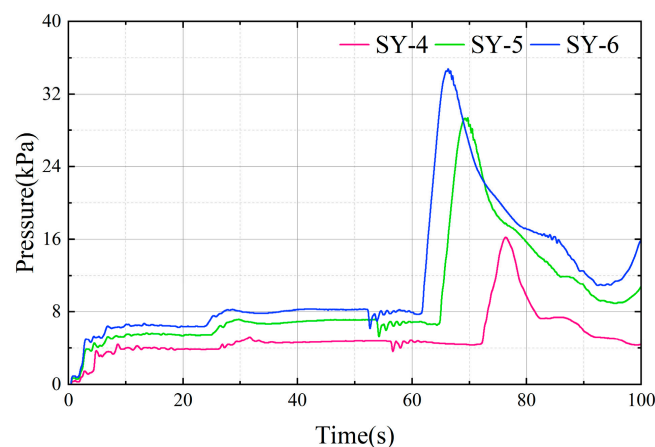


Figure 8. Temporal variation of pressure at the top of S-8# under different Stage-II flow rates with the Stage-I flow rate fixed at $1.0 \text{ m}^3/\text{s}$.

For Scenario SY-4, the pressure was generally maintained at a low level within the 0–70 s interval, predominantly concentrated within the 4–6 kPa range. Although an increase subsequently occurred, the peak value was merely 16 kPa. The pressure in Scenario SY-5 rose rapidly after 60 s and reached 29 kPa near 70 s, demonstrating a significant increase in peak pressure compared to SY-4. The pressure response in Scenario SY-6 was the most intense; it escalated rapidly after approximately 60 s and achieved a maximum level of 34 kPa around 65–70 s.

As the Stage II flow rate increased from $9 \text{ m}^3/\text{s}$ to $11 \text{ m}^3/\text{s}$, not only was the peak pressure at the top of S-8# significantly enlarged, but the triggering time of the high pressure was also markedly advanced. This result indicated that the downstream high-pressure sensitive region, where S-8# was located, was primarily governed by the intensity of the rapid filling in Stage II. A larger Stage II flow rate enhanced the flow advancement capability, accelerated the downstream development of hydraulic slugs, and intensified the compression of localized air pockets prior to the downstream diameter reduction, thereby

inducing a stronger extreme pressure response within a shorter timeframe. Consequently, the rapid filling flow rate in Stage II was identified as the dominant factor controlling the peak pressure at the top of S-8#, as well as the critical boundary condition determining the pressure risk level in the downstream high-pressure sensitive region.

In summary, the development process of pressure fluctuations and the timing of peak occurrences at S-3# are primarily modulated by the Stage I flow rate through alterations to the initial water level and the gas phase space distribution at the pipe crown. Conversely, the flow advancement intensity and the degree of gas compression during the rapid filling stage are directly controlled by the Stage II flow rate, which exerts a more stable and significant amplifying effect on the peak pressure in high-pressure sensitive regions. Particularly at S-8#, a significant increase in peak pressure and an advancement in triggering time are observed as the Stage II flow rate increases. This indicates that the region upstream of the downstream diameter reduction represents the most concentrated area of extreme pressure risk during the rapid filling process. Therefore, during the rapid filling process induced by intense rainfall, the extreme pressure response at the pipe crown is predominantly governed by the Stage II surge flow rate, whereas the Stage I flow rate primarily functions as a modulator of the initial gas phase structure and the localized pressure accumulation process.

4. Discussion

The pressure response during the rapid filling process of typical drainage pipelines is not a localized phenomenon of a single shaft or a single air pocket, but rather a global air–water linkage process governed jointly by main pipe filling advancement, branch pipe inflow disturbance, downstream reduced-diameter constraints, and manhole cover opening venting. As hydraulic slugs were formed and the gas phase space at the pipe crown was fragmented, localized air pockets underwent compression to form a high-pressure concentrated zone upstream of the downstream diameter reduction, which further induced a synchronous response in the midstream nodes. Meanwhile, although the manhole cover opening provided a pressure relief pathway, a delayed cycle of pressure accumulation, breakthrough, release, and re-accumulation still occurred within the shaft under the influence of localized water seals and continuous air supply. Therefore, discussions are conducted from three perspectives: global pipeline pressure linkage, restricted opening-mediated venting mechanisms, and engineering risk control.

The compression, migration, and release of entrapped air pockets during the rapid filling process are critical factors inducing transient pressure peaks and geysering phenomena [25–27]. These studies primarily focused on single pipe sections, single shafts, or specific air pocket motions, revealing the effects of air pocket dimensions, initial pressure, shaft boundaries, and air–water interface deformation on the pressure response. The present results are consistent with previous studies on entrapped-air compression, migration, and release during rapid filling. They further show that, in complex drainage sections with drop structures, branch inflows, and downstream reduced-diameter inverted siphons, the peak pressure does not necessarily attenuate monotonically along the flow direction. Instead, a high-pressure concentration zone can form upstream of the downstream diameter reduction and induce a feedback response in midstream nodes. Mechanistically, hydraulic slugs acted as moving local water seals that controlled both gas connectivity and pressure redistribution. Before obvious slug formation, the crown gas phase remained relatively connected in the longitudinal direction, and pressure disturbances generated by rapid filling could be transmitted over a wider region. This explains the early nearly synchronous pressure rise observed in several mid-to-downstream shafts. As the first and second hydraulic slugs formed near the branch-inflow regions, the originally continuous

crown gas space was divided into multiple confined air pockets. The longitudinal pressure equalization and continuous gas-release pathway were thereby weakened. Under this condition, the air pocket upstream of the downstream diameter reduction was compressed between the advancing water body and the downstream conveyance restriction, making it difficult to form a smooth venting pathway. Consequently, local pressure accumulated near S-8# rather than attenuating monotonically along the flow direction. This high-pressure region further affected adjacent midstream nodes through the connected main pipe–shaft system and the compression of neighboring air pockets, leading to pressure responses at S-5#, S-6#, and S-7#. Relevant studies on covered manholes have further indicated that the ventilation area of the manhole cover and the boundary conditions of the inspection chamber influence gas release, pressure accumulation, and geysering intensity [28,29]. Building upon this foundation, restricted opening-mediated venting was incorporated into the global pipeline air–water linkage process in this study. It was found that the manhole cover opening could not be simply equated to a sufficient venting boundary, and its pressure relief effectiveness was jointly restricted by hydraulic slug advancement, downstream boundary constraints, and localized water seals. This demonstrates that high-pressure risk assessment in practical engineering should not rely solely on the analysis of a single shaft or a single venting opening; rather, high-pressure sensitive nodes should be identified in conjunction with the global pipeline air–water linkage process.

Concurrently, shaft geysering is closely related to water column ascension, gas compression, and manhole cover ventilation conditions following the entry of air pockets into the shaft [28,30]. The results of this study echoed these findings and further demonstrated that a continuous and sufficient pressure relief process was not formed by the opening in manhole O-1#. When a water seal was formed at the shaft bottom and continuous air supply was provided by the main pipe, the bottom air pocket still repeatedly underwent a cycle of pressure accumulation, breakthrough, pressure relief, and re-accumulation, thereby inducing periodic delayed geysering. This delayed geysering mechanism differs from the early-stage high-pressure concentration upstream of the downstream diameter reduction. At O-1#, the pressure response was mainly governed by a vertical storage–breakthrough–resealing process inside the shaft. The manhole-cover openings mainly relieved pressure in the upper part of the shaft, whereas the bottom air pocket remained controlled by the local water seal and continuous air supply from the main pipe. When the bottom pressure became sufficiently high to overcome the resistance of the water seal, the trapped air pocket broke through the seal and drove an upward air–water surge. After partial gas release, the water level in the shaft receded; however, under the continuing inflow and local hydraulic conditions, the shaft bottom was resealed, initiating the next pressure accumulation cycle. Therefore, the delayed geysering at O-1# was not a single venting event, but a periodic air–water dynamic process controlled by continuous air supply, repeated water-seal reconstruction, and restricted opening-mediated venting. Compared with existing studies on geysering induced by air pocket migration [26,27], the present study places greater emphasis on the coupling effects among continuous air supply, localized water seals, and restricted opening venting within complex pipe sections. Chen et al. [29] pointed out that the ventilation area of the manhole cover, pressure head, and initial air pocket volume affect the geysering risk in covered manholes. However, in this study, the actual pressure relief effectiveness of the opening also depended on whether its venting capacity could match the gas supply rate within the main pipe. Therefore, the opening cannot be simply equated to a sufficient venting boundary. For nodes such as O-1#, which are prone to forming water seals and delayed geysering, emphasis should be placed on conducting venting capacity verification and localized anti-geysering design.

Although the present study varied only the Stage-I and Stage-II inflow rates, other geometric and hydraulic factors may also affect restricted venting and pressure response. The effective venting area is one of the most direct factors, but its influence is not necessarily monotonic. Increasing the opening area can enhance air release and reduce gas pressure in the upper shaft; however, it may also accelerate the upward motion of the air–water mixture and reduce the cushioning effect of the compressed air. Under some conditions, faster air expulsion may induce a more rapid water-column surge, and the subsequent impact of water or air–water mixtures near the manhole cover may increase the local impact-pressure risk. Therefore, increasing the venting area should not be interpreted simply as a monotonic pressure-reduction measure, but should be evaluated together with the risk of air–water mixture ejection. In addition, shaft diameter and depth affect gas storage volume, water-column inertia, and water-seal reconstruction; pipe roughness influences filling-front advancement, energy loss, and slug development; and pipe slope affects air-pocket migration, retention, and the formation of local water seals. These factors were kept consistent with the prototype drainage section in the present study to focus on the air–water linkage mechanism under surveyed rapid-filling flow conditions. Their coupled influence should be examined through dedicated parametric simulations or combined physical-model and numerical-model studies in future work.

Furthermore, the results of this study not only revealed the pressure formation mechanism during the rapid filling process but also provided a hydraulic basis for identifying manhole cover bounce and near-field safety risks. Based on prototype-scale dual-shaft experiments, Zhao et al. [31] indicated that a critical overpressure existed for the initial lift-off of manhole covers, and this threshold increased with the addition of counterweights. Meanwhile, van de Meulenhof et al. [32] explained the cover lift-off, reseating, and secondary bounce processes from the perspective of hinged manhole cover dynamics. Compared with these studies, manhole cover motion was not directly simulated in the present study; instead, the in-pipe air–water transient sources inducing manhole cover risks were further traced—specifically, how hydraulic slug advancement, air pocket compression prior to the downstream diameter reduction, and restricted opening venting jointly formed localized overpressure. Furthermore, the three-dimensional numerical modeling of geyser formation by Chan et al. [33], the shaft geyser experiments of Allasia et al. [34], and the analyses of large air pocket transport by Molina and Ortiz [35] all demonstrated that the compression, propagation, and release pathways of air pockets significantly affect the system pressure response. The present study bridges with these works: high-pressure sensitive nodes such as S-8# correspond to pressure risk sources, whereas delayed geysering nodes such as O-1# correspond to restricted venting and water seal circulation locations. Therefore, mitigating the risk of manhole cover bounce in practical engineering should not rely solely on terminal protection via counterweights or locking structures; high-pressure formation sources and weak venting nodes should also be identified from within the pipe sections. The results of this study can provide criteria for the closed-loop modification of source entrapped-air control, critical node venting optimization, anti-bounce design of manhole covers, and pressure monitoring and early warning systems.

5. Conclusions

In this study, a three-dimensional unsteady air–water two-phase flow model is established to analyze the global pipeline air–water linkage, restricted opening-mediated venting, and pressure responses under various flow rate conditions during the rapid filling process of typical urban drainage pipelines. The main conclusions are summarized as follows:

1. During the rapid filling process, the continuous gas phase space at the pipe crown is fragmented into multiple localized air cavities by hydraulic slugs, and the region upstream of the downstream diameter reduction becomes a high-pressure concentrated zone. Under representative high-flow rate scenarios, the maximum pressure at the top of the shaft is approximately 29.2 kPa, and the peak pressures of multiple mid-to-downstream shafts exceed 20 kPa. This indicates that the pressure response does not simply attenuate along the flow direction; instead, it is jointly governed by branch pipe inflows, slug advancement, and downstream reduced-diameter constraints, exhibiting pronounced spatial linkage characteristics.
2. Opening-mediated venting cannot be simply equated to continuous and sufficient pressure relief. Following the initial global compression within localized shafts, the top pressure can decrease rapidly due to opening-mediated venting, whereas the bottom air pocket remains governed by the water seal and gas supply from the main pipe, resulting in a significant vertical pressure gradient. In the later stages, the shaft pressure repeatedly rebounds to 20 kPa with an interval of approximately 110–120 s between adjacent peaks, which demonstrates that the cycle of pressure accumulation, breakthrough, pressure relief, and re-accumulation constitutes the critical mechanism for the formation of delayed geysering.
3. The rapid filling flow rate in Stage II exerts the most significant controlling effect on the peak pressure within high-pressure sensitive regions. When the Stage I flow rate is maintained at 1.0 m³/s, as the Stage II flow rate increases from 9 m³/s to 10 m³/s and 11 m³/s, the peak pressures at the top of the representative downstream shaft rise from approximately 16 kPa to 29 kPa and 34 kPa, respectively, accompanied by an advanced triggering time for the high pressure. This further indicates that the rapid filling intensity directly determines the compression rate of the downstream air pocket and the outbreak intensity of the high pressure, serving as a boundary condition that must be prioritized in venting capacity verification and anti-geysering design.

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