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Geological controls and migration mechanisms of gas in fractured non-coal-measure strata: Insights from mountainous tunnel investigations in the western Sichuan Plateau

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Abstract: Gas migration through fractured geological media is controlled by the coupled effects of gas sources, geological structures, and excavation-induced disturbances. However, the occurrence patterns and migration mechanisms of gas in non-coal-measure fractured strata remain poorly understood, particularly in mountainous regions with complex tectonic conditions. This study investigates gas occurrence and migration characteristics in representative non-coal-measure tunnels located in the western Sichuan Plateau, China, by integrating field investigation, geological interpretation, gas monitoring, and three-dimensional numerical modelling. Based on engineering

geological observations, three typical gas occurrence patterns are identified, including direct exposure of gas-bearing strata, structural connection between deep gas sources and underground openings, and indirect exposure through secondary migration pathways. A geological source-pathway-opening framework is proposed to describe the progressive process of gas accumulation and migration under excavation disturbance. A three-dimensional gas transport model is subsequently established to quantify the effects of exposed gas-bearing areas and gas-conducting structures on the spatial distribution and migration behavior of gas. The results indicate that gas migration is strongly controlled by the connectivity of geological pathways and the interaction between gas pressure gradients and excavation-induced openings. Larger exposed gas-bearing areas and more favorable structural pathways significantly enhance local gas accumulation and accelerate migration toward underground openings. Field monitoring results from a representative tunnel further verify the reliability of the proposed migration mechanism and numerical analysis. This study provides new insights into gas migration in fractured non-coal-measure geological media and offers a geological framework for evaluating gas-related risks in deep underground engineering.

Keywords: fractured geological media; gas migration; non-coal-measure strata; geological controls; underground engineering; numerical modelling

1 Introduction

Gas migration in fractured geological media is a complex transport process involving interactions among geological structures, pore-fracture systems, stress conditions, and fluid properties [1-12]. Such processes are closely associated with subsurface energy exploitation, underground engineering safety, and geological hazard prevention [13-26]. Compared with homogeneous porous media, fractured

44 geological formations exhibit strong heterogeneity and anisotropy due to the existence of faults,
45 fractures, bedding planes, and structural discontinuities. These geological features can either enhance
46 or restrict gas migration by controlling preferential flow pathways, pressure redistribution, and local
47 accumulation behavior. Therefore, understanding the mechanisms governing gas migration in fractured
48 geological media is essential for evaluating subsurface fluid transport and improving the safety of
49 underground engineering systems [21-30].

50 Previous studies have demonstrated that gas migration in fractured rocks is controlled by multiple
51 coupled mechanisms, including seepage, diffusion, adsorption-desorption, and fracture deformation.
52 In coal-bearing geological systems, gas transport has been extensively investigated due to its
53 importance in energy recovery and mining safety. Zhou et al. [10] established a coal mine gas migration
54 model and investigated gas extraction behavior under field conditions, demonstrating the importance
55 of geological conditions and pressure gradients in controlling gas transport. Liu et al. [16] investigated
56 the effective diffusion coefficient of gas in water-saturated coal through combined modelling and
57 experiments, revealing the significant influence of diffusion characteristics on gas migration. Song et
58 al. [15] further analyzed damage evolution and precursor responses during gas-bearing coal failure,
59 indicating that mechanical damage processes strongly influence gas transport characteristics.

60 The permeability evolution of fractured geological media is a critical factor controlling gas
61 migration. Fracture geometry, pore structure, and stress-dependent deformation determine the
62 connectivity of migration pathways and the efficiency of gas transport. Liu et al. [11] proposed a
63 fracture-pore fractal model for coal gas seepage based on structural characteristics, emphasizing the
64 influence of pore-fracture systems on gas flow behavior. Gao et al. [23] reviewed existing coal
65 permeability models and highlighted the necessity of considering coupled mechanical and transport

66 processes in gas migration analysis. Tian et al. [29] developed an effective stress-dependent dual-
67 fractal permeability model considering multiple flow mechanisms, demonstrating the coupling
68 relationship between stress evolution and gas transport. Liu et al. [27] further improved gas seepage
69 modelling by incorporating fracture-pore structural characteristics into permeability descriptions.

70 In addition to permeability evolution, fluid-solid coupling and geological disturbance
71 significantly affect gas migration behavior. Zhang et al. [12] developed a dynamic multifield coupling
72 model for gas drainage and investigated the interaction between mechanical deformation and gas
73 transport. Liu et al. [24] established a dual-porosity gas migration model around boreholes and
74 analyzed the effects of different driving forces on gas movement. Zhao et al. [25] investigated the
75 critical stress associated with coalbed methane migration patterns and demonstrated the influence of
76 stress conditions on migration transitions. Yuan et al. [30] further considered thermo-hydro-mechanical
77 coupling effects during gas emission and proposed a theoretical model for dynamic gas migration.

78 Although substantial progress has been achieved in gas migration research for coal seams and
79 energy-related geological systems, gas transport mechanisms in non-coal-measure fractured strata
80 remain insufficiently understood. Unlike conventional coalbed methane systems, gas occurrence in
81 non-coal geological environments is commonly controlled by complex geological structures, including
82 carbonaceous rocks, faults, fractures, and structural zones. In such environments, gas sources may not
83 directly coincide with underground openings but may migrate through interconnected geological
84 pathways. The interaction between gas sources, structural migration channels, and excavation-induced
85 openings may result in localized and intermittent gas accumulation phenomena.

86 Recent studies have demonstrated that excavation activities can significantly modify the
87 mechanical and transport properties of fractured geological media. Song et al. [17] investigated

88 permeability evolution and structural failure mechanisms of fractured sandstone under fluid-solid
89 coupling, considering excavation unloading effects, highlighting the role of disturbance-induced
90 fracture evolution in controlling permeability. Tan et al. [18] further analyzed failure mechanisms and
91 permeability evolution in gas-bearing strata under tunnel-induced stress paths, demonstrating the
92 influence of excavation disturbance on gas migration. Zhang et al. [22] investigated water and gas
93 inrush mechanisms during tunnel excavation and emphasized the controlling role of geological
94 structures in fluid migration processes.

95 Mountainous underground engineering projects provide valuable opportunities to investigate gas
96 migration within naturally fractured geological systems. The western Sichuan Plateau, located at the
97 eastern margin of the Tibetan Plateau, is characterized by intense tectonic deformation, complex fault
98 systems, and highly fractured rock masses. Gas occurrence in this region is not limited to conventional
99 coal-bearing formations but may also occur in non-coal-measure strata associated with structural
100 discontinuities. Previous tunnel studies have shown that geological structures and fracture
101 characteristics strongly influence underground fluid migration. Shahbazi et al. [4] established an index
102 considering fracture length and aperture to predict groundwater inflow in fractured-rock tunnels,
103 demonstrating the importance of fracture geometry in controlling subsurface fluid transport. Liu et al.
104 [19] investigated nonlinear seepage fields in tunnels under different computational models and
105 boundary conditions, providing insights into fluid migration modelling in underground structures.
106 Chen et al. [21] further studied active drainage methods for groundwater environment protection and
107 tunnel safety control.

108 Numerical modelling has become an effective approach for investigating complex underground
109 transport and mechanical behaviors. Recent studies have developed analytical and numerical methods

110 to characterize underground structures under complicated geological and loading conditions. Lu et al.
111 [1,3,5,14,20] established analytical and experimental frameworks for evaluating tunnel and
112 underground structure responses considering joints, faults, and heterogeneous geological conditions.
113 These studies provide valuable methodological references for incorporating structural discontinuities
114 and geological constraints into underground engineering analysis. In addition, Zhou et al. [6-9]
115 investigated ventilation, dust, and gas-bearing flow behaviors in underground excavation environments,
116 demonstrating the importance of numerical approaches for evaluating complex transport processes.

117 Despite these advances, a systematic understanding of gas occurrence patterns and geological
118 migration mechanisms in non-coal-measure fractured strata remains lacking. In particular, the coupling
119 relationship among gas sources, geological migration pathways, and excavation-induced openings has
120 not been fully clarified. Existing studies mainly focus on gas extraction, coal mining, or individual
121 engineering control measures, whereas the geological mechanisms controlling gas migration in
122 complex underground openings require further investigation.

123 Therefore, this study investigates gas occurrence and migration mechanisms in representative
124 non-coal-measure tunnels in the western Sichuan Plateau by integrating geological investigation, field
125 monitoring, and three-dimensional numerical modelling. Three typical gas occurrence patterns are
126 identified based on geological characteristics and engineering observations. A geological source-
127 pathway-opening framework is proposed to describe gas migration processes under excavation
128 disturbance. Furthermore, the effects of exposed gas-bearing areas and gas-conducting structures on
129 gas transport behavior are quantitatively evaluated through numerical simulations, and field
130 monitoring results are used to verify the proposed mechanism. The findings provide new insights into
131 fracture-controlled gas migration in complex geological media and contribute to the understanding of

132 subsurface fluid transport processes in deep underground environments.

133 **2 Engineering Background and Field Observations**

134 **2.1 Regional Engineering Setting**

135 The western Sichuan Plateau is located in a high-altitude mountainous region with strong topographic
136 relief, complex tectonic structures, and variable lithological assemblages. The construction of the
137 Jiuzhi-Maerkang and Wenchuan-Maerkang expressways has significantly improved regional
138 transportation, but it has also introduced a series of geological safety challenges during tunnel
139 excavation. Among them, gas inflow in non-coal-measure strata is a representative problem because it
140 may occur suddenly even in formations that are not conventionally classified as coal-bearing strata.

141 During the construction of the Jiuzhi-Maerkang and Wenchuan-Maerkang expressways, several
142 tunnels were found to exhibit gas inflow, gas burning, or abnormal gas concentration. Representative
143 gas-related tunnels include Linchang Tunnel and Sanjiazhai Tunnel on the Jiuzhi-Maerkang
144 Expressway, and Wangjiazhai Tunnel, Miyaluo No. 3 Tunnel, and Zhegushan Tunnel on the
145 Wenchuan-Maerkang Expressway. Among these tunnels, Wangjiazhai Tunnel and Miyaluo No. 3
146 Tunnel were identified as high-gas tunnels, whereas Linchang Tunnel and Sanjiazhai Tunnel were
147 identified as low-gas tunnels. Several other tunnels were classified as micro-gas tunnels. The location
148 of Sichuan Province and the spatial distribution of representative gas-related tunnels along the Jiuzhi-
149 Maerkang and Wenchuan-Maerkang expressways are shown in Fig. 1.

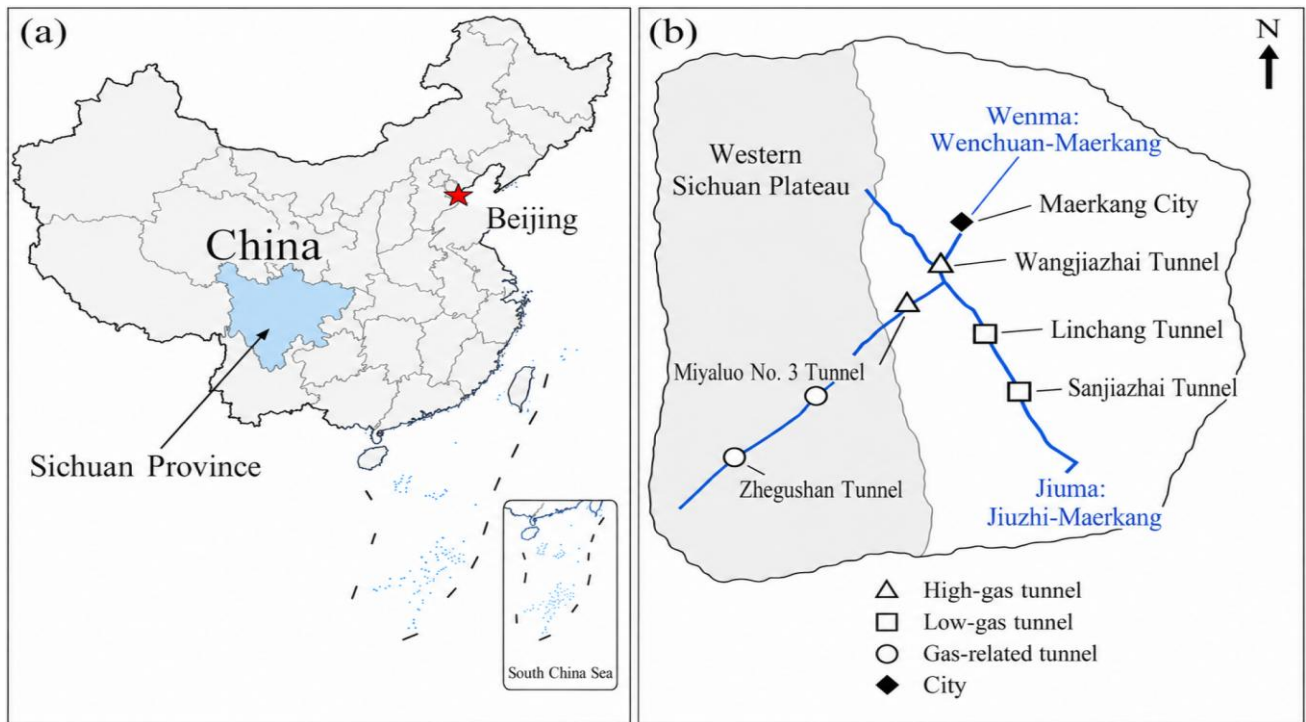


Fig. 1 Location of the study area and distribution of representative gas-related highway tunnels in the western Sichuan Plateau: (a) location of the study area in China; and (b) distribution of representative tunnels in the western Sichuan Plateau.

The strata crossed by these tunnels are mainly metamorphic sandstone, slate, carbonaceous phyllite, and interbedded metamorphic sandstone and slate belonging to the Triassic Xikang Group and related formations. These formations are not typical coal-measure strata. However, local carbonaceous phyllite, slate, fractured metamorphic rocks, and structural zones may still provide hydrocarbon-generating conditions or gas migration pathways. Therefore, gas hazards in this region cannot be evaluated solely using the conventional concept of continuous coal-seam gas occurrence.

2.2 Linchang Tunnel as the Engineering Case

Linchang Tunnel is located near Wangjiazhai, Maerkang City of Sichuan, and is close to the terminal section of the Jiuzhi-Maerkang Expressway. The original design length is 1263 m for the left tunnel

164 and 1338 m for the right tunnel. The maximum burial depth is approximately 195 m. The design
165 elevation of the tunnel ranges from 3095 m to 3070 m. Because of the high-altitude environment, the
166 tunnel is affected by low temperature conditions, and thermal insulation measures were considered in
167 the original design for the secondary lining and drainage ditch.

168 The tunnel site is located in a middle- to high-mountain canyon slope area. The terrain is relatively
169 steep, with the entrance-side slope generally ranging from 38° to 48° and the exit-side slope ranging
170 from 35° to 40°. Geological investigation and drilling indicate that the strata exposed in the tunnel area
171 include Quaternary colluvial deposits and Triassic metamorphic sandstone, slate interbeds, and
172 metamorphic sandstone intercalated with slate. The surrounding rock is mainly classified as Grade V
173 and Grade IV, accounting for 62.78% and 37.22%, respectively. These geological conditions indicate
174 that the tunnel passes through fractured and relatively weak rock masses, which may provide favorable
175 migration channels for gas released from local gas-bearing strata or gas-conducting structures.

176 The tunnel was originally designed as a micro-gas tunnel, but the design required strengthened
177 gas monitoring and advance probe drilling. This design background reflects a typical feature of non-
178 coal-measure gas tunnels: although the tunnel does not pass through conventional coal seams, local
179 gas occurrence cannot be completely excluded because of the uncertainty of gas-bearing structures and
180 gas migration pathways.

181 **2.3 Gas Occurrence in Representative Non-Coal-Measure Tunnels**

182 Field evidence from the Jiuzhi-Maerkang and Wenchuan-Maerkang expressways shows that gas
183 occurrence in non-coal-measure highway tunnels is spatially discontinuous and strongly controlled by
184 local geological conditions. Gas may occur in fractured zones, carbonaceous lithological units,

185 structural belts, or deep gas-conducting pathways. The gas occurrence characteristics of representative
 186 non-coal-measure highway tunnels in the western Sichuan Plateau are summarized in Table 1.

187 Table 1 Gas occurrence characteristics of representative non-coal-measure highway tunnels in the
 188 western Sichuan Plateau

Tunnel	Expressway	Gas grade	Main geological condition	Typical gas occurrence characteristic	Engineering implication
Wangjiazhai Tunnel	Wenchuan-Maerkang Expressway	High-gas tunnel	Non-coal-measure strata affected by complex geological structures	Significant gas occurrence was encountered during tunnel construction	High gas risk may occur even without coal-measure strata
Miyaluo No. 3 Tunnel	Wenchuan-Maerkang Expressway	High-gas tunnel	Non-coal-measure strata with gas-bearing or gas-conducting geological conditions	Gas inflow or a gas-related abnormality was observed during excavation	Gas migration is strongly controlled by structural pathways
Linchang Tunnel	Jiuzhi-Maerkang Expressway	Low-gas tunnel	Interbedded metamorphic sandstone and slate; maximum burial depth of approximately 195 m	Localized gas occurrence was observed, showing a spatially nonuniform gas distribution	Used as the main case for field-based simulation and monitoring analysis
Sanjiazhai Tunnel	Jiuzhi-Maerkang Expressway	Low-gas tunnel	Non-coal-measure strata with local gas-bearing geological conditions	Local gas occurrence was identified during construction	Low-gas tunnels may still contain local gas-accumulation zones

189 The geological profiles and measured gas occurrence information of representative tunnels are
 190 summarized in Fig. 2, including Sanjiazhai Tunnel, Linchang Tunnel, and Miyaluo No. 3 Tunnel.
 191 Unlike coal-measure tunnels, where gas sources are often associated with relatively continuous coal
 192 seams, non-coal-measure gas tunnels may experience gas inflow only when excavation exposes
 193 specific gas-bearing or gas-conducting geological bodies.

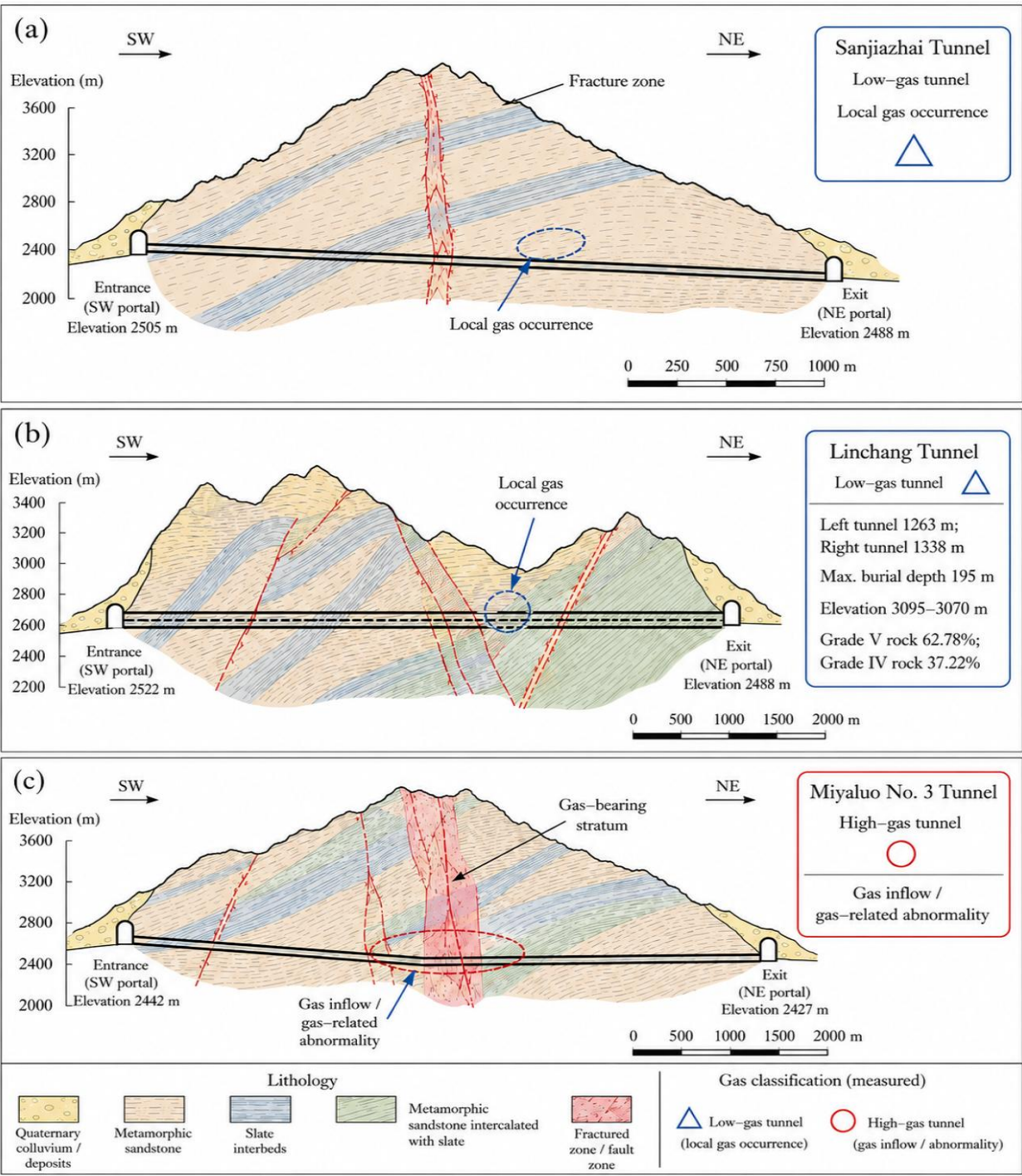


Fig. 2 Geological profiles and gas occurrence characteristics of representative non-coal-measure highway tunnels in the western Sichuan Plateau: (a) Sanjiazhai Tunnel; (b) Linchang Tunnel; and (c) Miyaluo No. 3 Tunnel.

Based on field investigation and engineering cases, three gas occurrence patterns can be generalized.

200 The first pattern is direct exposure of hydrocarbon-generating strata. In this case, tunnel
 201 excavation directly cuts through lithological units with a certain hydrocarbon-generating capacity, such
 202 as carbonaceous slate or carbonaceous phyllite. Gas stored in the pores, microfractures, or bedding
 203 planes of these strata is released into the tunnel after excavation unloading.

204 The second pattern is connection between deep gas reservoirs and the tunnel through gas-
 205 conducting structures. In this case, the gas source may not be located immediately around the tunnel.
 206 Instead, faults, fractures, or structural belts connect deeper gas-bearing zones with shallow rock masses.
 207 Once tunnel excavation intersects such gas-conducting structures, gas may migrate rapidly into the
 208 tunnel along the pressure gradient.

209 The third pattern is indirect exposure of gas-source structures. In this case, tunnel excavation does
 210 not directly intersect the primary gas-bearing body but disturbs nearby gas-bearing structural zones or
 211 secondary migration pathways. Gas may subsequently migrate toward the tunnel through fractures,
 212 weak structural planes, or partially connected porous-fractured media, resulting in localized,
 213 intermittent, or delayed gas inflow at specific positions.

214 Based on field observations and geological interpretations of representative tunnels, gas
 215 occurrence and inflow patterns in non-coal-measure highway tunnels can be classified into three types,
 216 as summarized in Table 2.

217 Table 2 Classification of gas occurrence and inflow patterns in non-coal-measure highway tunnels

Pattern	Gas source	Main migration pathway	Excavation-triggered condition	Typical inflow characteristic	Engineering concern
Pattern I: Direct exposure of hydrocarbon-generating strata	Gas-bearing hydrocarbon-generating strata or organic-rich rock	Short-distance seepage from the exposed gas-bearing rock mass	The tunnel face directly cuts through gas-bearing strata	Gas enters the tunnel from the exposed rock surface and is mainly concentrated	Local high-concentration gas may occur near the tunnel face or

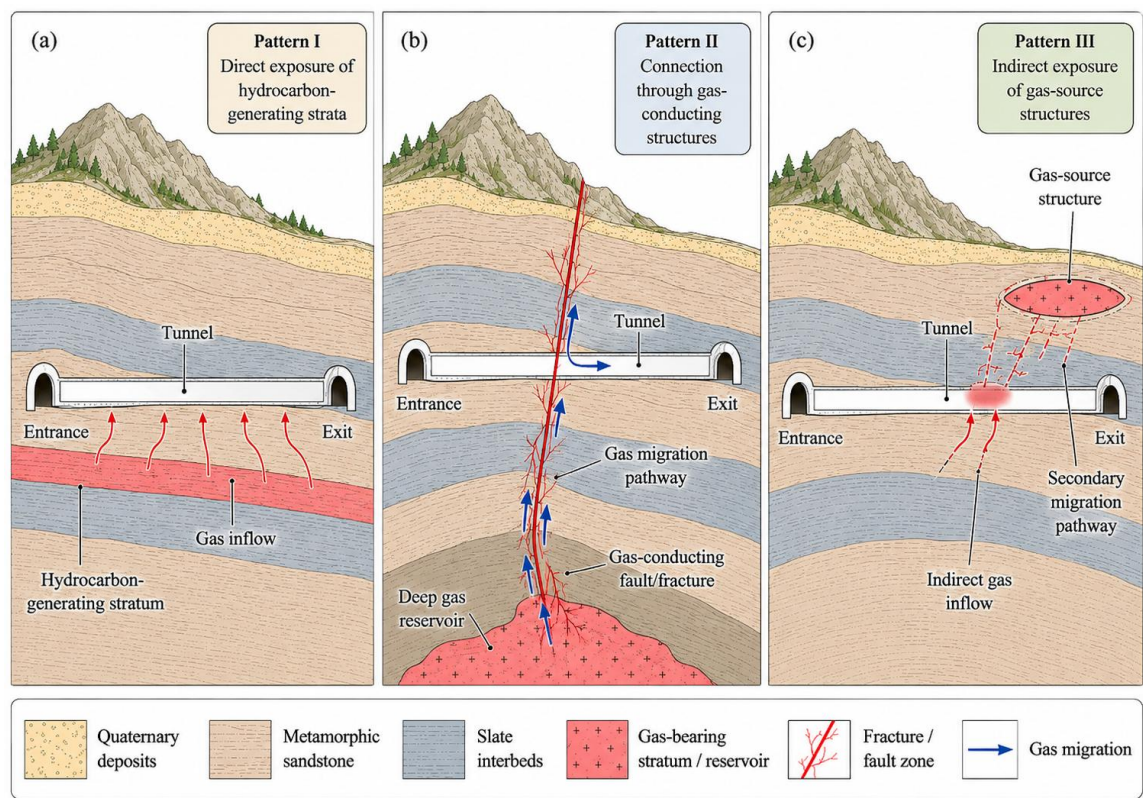
	layers			near the exposed region	sidewall
Pattern II: Connection with deep gas reservoirs through gas-conducting structures	Deep gas reservoirs or confined gas- bearing zones	Faults, fracture zones, bedding planes, or other gas-conducting structures	Excavation intersects or approaches a gas- conducting structure connected to a deep gas source	Gas inflow is concentrated along structural interfaces and may increase rapidly after the pathway is opened	Sudden gas inflow and structurally controlled gas migration may occur
Pattern III: Indirect exposure of gas-source structures	Local gas pockets, weakly connected gas-bearing zones, or gas-enriched fracture networks	Secondary fractures, discontinuous joints, or partially connected porous- fractured media	Excavation disturbs nearby gas-bearing structures without fully exposing the primary gas source	Gas release is discontinuous, delayed, and spatially nonuniform	Hidden gas accumulation zones may form away from the initial gas-source position

The conceptual interpretation of these three gas occurrence patterns is further illustrated in Fig. 3, and their common controlling mechanism can be generalized as a source-pathway-opening framework, as shown in Fig. 4.

The third pattern is indirect exposure of gas-source structures. In this case, tunnel excavation does not directly expose a major gas reservoir, but it disturbs local gas-bearing structural zones or secondary migration pathways. This may result in localized gas inflow, intermittent gas concentration increase, or sudden gas release at specific positions along the tunnel.

These three patterns indicate that gas hazards in non-coal-measure tunnels are controlled by the combined effect of gas source, migration pathway, and excavation opening. Therefore, gas hazard prediction should not only identify whether the strata are coal-bearing but also evaluate hydrocarbon-generating lithology, gas-conducting faults, fractured zones, and the spatial relationship between these geological bodies and the tunnel alignment. The conceptual gas occurrence patterns in non-coal-measure highway tunnels are illustrated in Fig. 3, including direct exposure of hydrocarbon-generating strata, connection with deep gas reservoirs through gas-conducting structures, and indirect exposure

232 of gas-source structures.



233
234 Fig. 3 Conceptual gas occurrence patterns in fractured non-coal-measure geological media: (a) direct
235 exposure of gas-bearing strata; (b) structural connection between deep gas sources and underground
236 openings; and (c) indirect migration through secondary geological pathways.

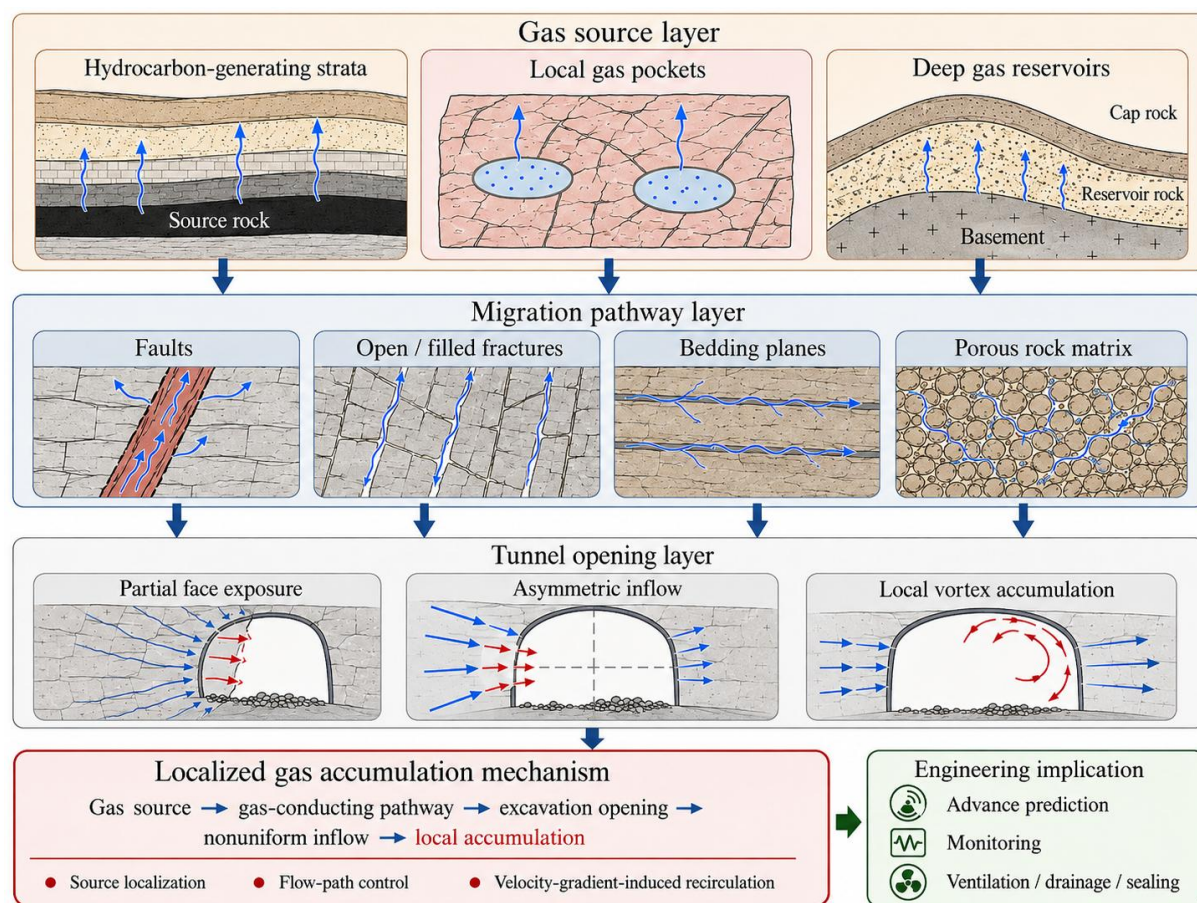
237 3 Theoretical Framework and Numerical Modeling

238 3.1 Source-pathway-opening Framework

239 For non-coal-measure highway tunnels, the gas inflow process can be generalized as a source-pathway-
240 opening system. The gas source may be a local hydrocarbon-generating stratum, a gas pocket in
241 fractured rock, or a deeper gas reservoir. The migration pathway may consist of faults, open fractures,
242 partially filled fractures, bedding planes, or porous rock matrix. The tunnel face or tunnel wall acts as
243 the excavation opening that changes the original gas pressure equilibrium and provides a low-pressure

244 boundary for gas migration.

245 The source-pathway-opening mechanism of gas inflow and localized accumulation in non-coal-
 246 measure highway tunnels is schematically illustrated in Fig. 4.



247

248 Fig. 4 Geological source-pathway-opening framework for gas migration in fractured non-coal-
 249 measure strata under excavation disturbance.

250 Before excavation, gas in the rock mass may remain in a relatively stable state under in situ stress
 251 and pore pressure. After excavation, the tunnel space becomes a low-pressure boundary. If the
 252 excavation face intersects a gas-bearing stratum or a gas-conducting structure, the original pressure
 253 balance is disturbed. Gas then migrates toward the tunnel along the pressure gradient. The inflow
 254 intensity and spatial distribution depend on the size of the exposed gas-bearing area, permeability of
 255 the migration pathway, gas pressure, fracture filling condition, and tunnel ventilation conditions.

256 In this study, the source-pathway-opening framework is used to interpret the field observations
257 and guide the numerical case design. The exposed gas-bearing area represents the source-opening
258 relationship, while the gas-conducting fault attitude represents the pathway-opening relationship.
259 These two factors are selected as the main variables for numerical simulation.

260 **3.2 Governing Equations for Gas Flow**

261 Gas migration in the tunnel space and gas-conducting structures can be described using a continuum
262 fluid mechanics framework. In open tunnel space and open fractures, gas flow is treated as viscous
263 free flow. For an incompressible Newtonian gas under steady-state conditions, the continuity equation
264 can be expressed as

$$265 \quad \nabla \cdot \mathbf{u} = 0 \quad (1)$$

266 where $\nabla \cdot \mathbf{u}$ is the gas velocity vector.

267 The momentum equation for free gas flow can be written as

$$268 \quad \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} \quad (2)$$

269 where ρ is the gas density, p is the gas pressure, and μ is the dynamic viscosity.

270 For gas seepage in porous rock matrix or filled fractures, the Brinkman-extended Darcy equation
271 can be used to describe the combined effect of viscous shear and porous resistance:

$$272 \quad -\nabla p + \mu_e \nabla^2 \mathbf{u} - \frac{\mu}{k} \mathbf{u} = 0 \quad (3)$$

273 where k is the permeability of the porous medium and μ_e is the effective viscosity.

274 At the interface between an open fracture and a porous matrix, velocity continuity and shear stress
275 compatibility should be satisfied:

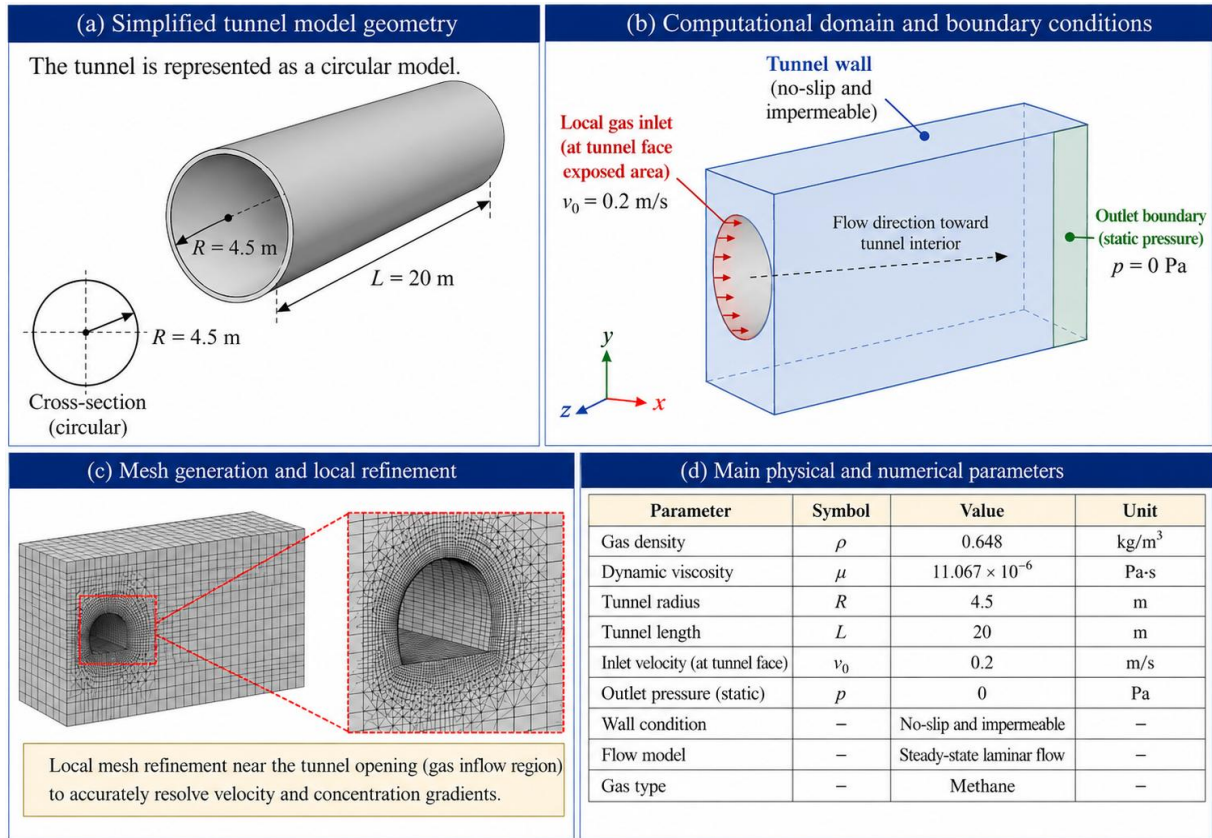
$$276 \quad \mathbf{u}^f = \mathbf{u}^m \quad (4)$$

277
$$\tau_f = \tau_m \quad (5)$$

278 where the subscripts f and m denote the fracture domain and matrix domain, respectively. These
279 equations provide a simplified theoretical basis for explaining why open, filled, and partially filled
280 fractures may show different gas-conducting capacities. In the present paper, the governing equations
281 are used primarily to support the tunnel-scale flow interpretation, while the detailed fracture-scale
282 analytical solution is outside the scope of this work.

283 **3.3 Numerical Model for Tunnel Gas Dispersion**

284 A three-dimensional numerical model was established in COMSOL Multiphysics using the finite
285 element method to simulate gas migration after tunnel excavation. Considering the circular
286 characteristics of the tunnel section and the need to reduce computational cost while retaining the
287 principal flow features, the tunnel was simplified as a cylindrical domain with a radius of 4.5 m and a
288 length of 20 m. The model was used to analyze the flow field after gas enters the tunnel from exposed
289 gas-bearing strata or gas-conducting structures. The numerical model, boundary conditions, mesh
290 generation, and main simulation parameters are shown in Fig. 5.



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Fig. 5 Numerical model setup for gas migration analysis in non-coal-measure highway tunnels: (a) simplified tunnel geometry; (b) computational domain and boundary conditions; (c) mesh generation and local refinement; and (d) main physical and numerical parameters.

The numerical analysis was conducted under steady-state laminar flow conditions. The gas was treated as a Newtonian fluid. The inlet boundary was assigned a prescribed gas inflow velocity of 0.2 m/s for the general tunnel-face exposure cases, and the outlet boundary was set as a static pressure boundary with a pressure of 0 Pa. The tunnel wall was treated as a no-slip and impermeable boundary. The boundary-condition types, typical gas-inflow configurations near the tunnel opening, computational domain, and mesh-refinement strategy are further illustrated in Fig. 6.

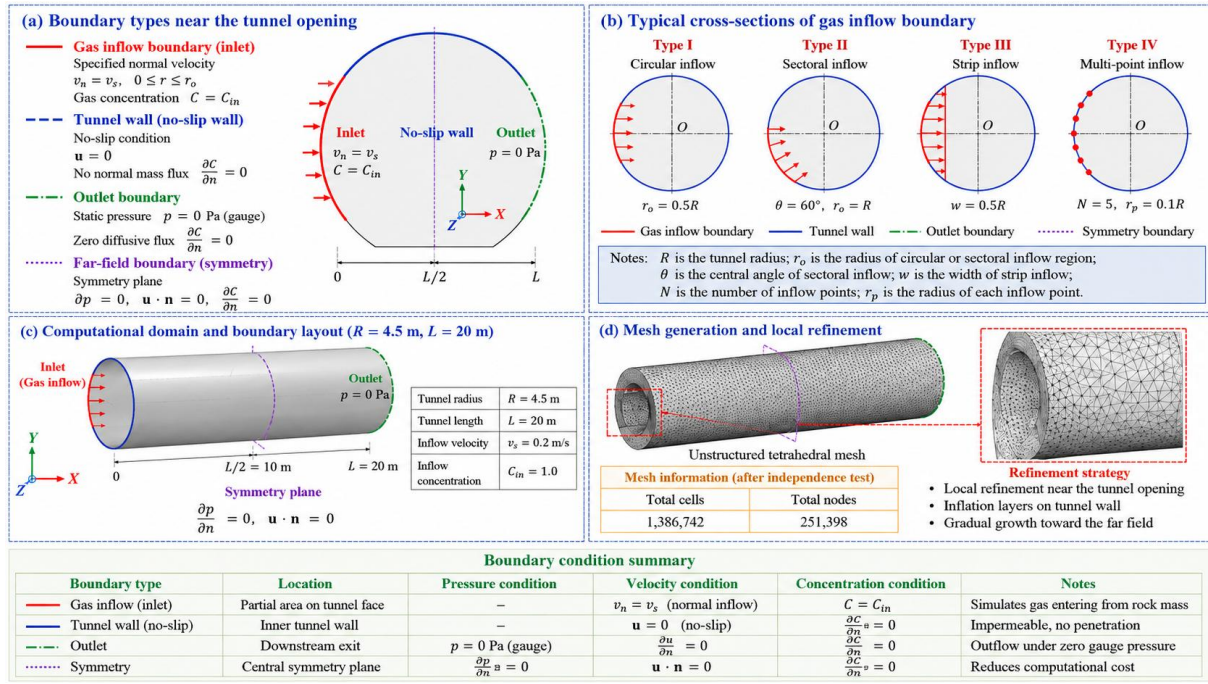


Fig. 6 Schematic illustration of gas migration under different exposed gas-bearing areas at the tunnel face: (a) one-third exposed area; (b) one-half exposed area; and (c) two-thirds exposed area.

The density and dynamic viscosity of methane were taken as 0.648 kg/m^3 and $11.067 \times 10^{-6} \text{ Pa} \cdot \text{s}$, respectively.

The numerical analysis focused on the spatial distribution of gas velocity, streamlines, and local vortex zones. These flow-field indicators were used to identify potential high-risk regions of gas migration and accumulation near the tunnel face.

3.4 Simulation Cases

Two groups of numerical cases were designed. The first group was used to investigate the effect of the exposed gas-bearing area at the tunnel face. In practical excavation, gas-bearing strata may not occupy the entire tunnel face. Instead, only a local part of the face may intersect a gas-bearing layer. Therefore, three exposed-area ratios were considered: one-third, one-half, and two-thirds of the tunnel face. These cases were used to evaluate how the gas-affected region expands as the exposed source area increases.

316 The second group was used to investigate the influence of gas-conducting fault attitude. During tunnel
317 excavation, a fault may intersect the tunnel face at different attitudes. According to the relationship
318 between the fault and the tunnel excavation direction, three conditions were considered: fault dipping
319 toward the tunnel face, vertical fault, and fault dipping away from the tunnel face. The inclined fault
320 cases represent local early exposure of a gas-conducting structure, whereas the vertical fault case
321 represents a larger contact area between the gas-conducting structure and the tunnel face.

322 The numerical simulation cases for exposed gas-bearing strata and gas-conducting faults are
323 summarized in Table 3.

324 Table 3 Numerical simulation cases

Case group	Case ID	Geological condition	Exposed area or fault attitude	Main purpose
Exposed gas-bearing strata	A1	Local exposure	1/3 of tunnel face	Small-scale exposed gas source
Exposed gas-bearing strata	A2	Local exposure	1/2 of tunnel face	Medium-scale exposed gas source
Exposed gas-bearing strata	A3	Local exposure	2/3 of tunnel face	Large-scale exposed gas source
Gas-conducting fault	B1	Inclined fault	Dipping toward the tunnel face	Localized early-stage exposure
Gas-conducting fault	B2	Vertical fault	Orthogonal to excavation direction	Large inflow interface
Gas-conducting fault	B3	Inclined fault	Dipping away from the tunnel face	Delayed localized exposure

325 This case design allows the migration characteristics of gas in non-coal-measure tunnels to be
326 examined from two perspectives: local exposure of gas-bearing strata and structural connection with
327 deeper gas sources. The former corresponds mainly to direct exposure of hydrocarbon-generating
328 strata, whereas the latter corresponds mainly to gas migration through gas-conducting structures.

4 Results and Discussion

Before analyzing individual cases, the influence of the exposed gas-bearing area at the tunnel face was first compared. Three exposure ratios were considered, namely one-third, one-half, and two-thirds of the tunnel face, representing small, medium, and large local gas-source exposure conditions, respectively. The corresponding gas velocity distributions are shown in Fig. 7.

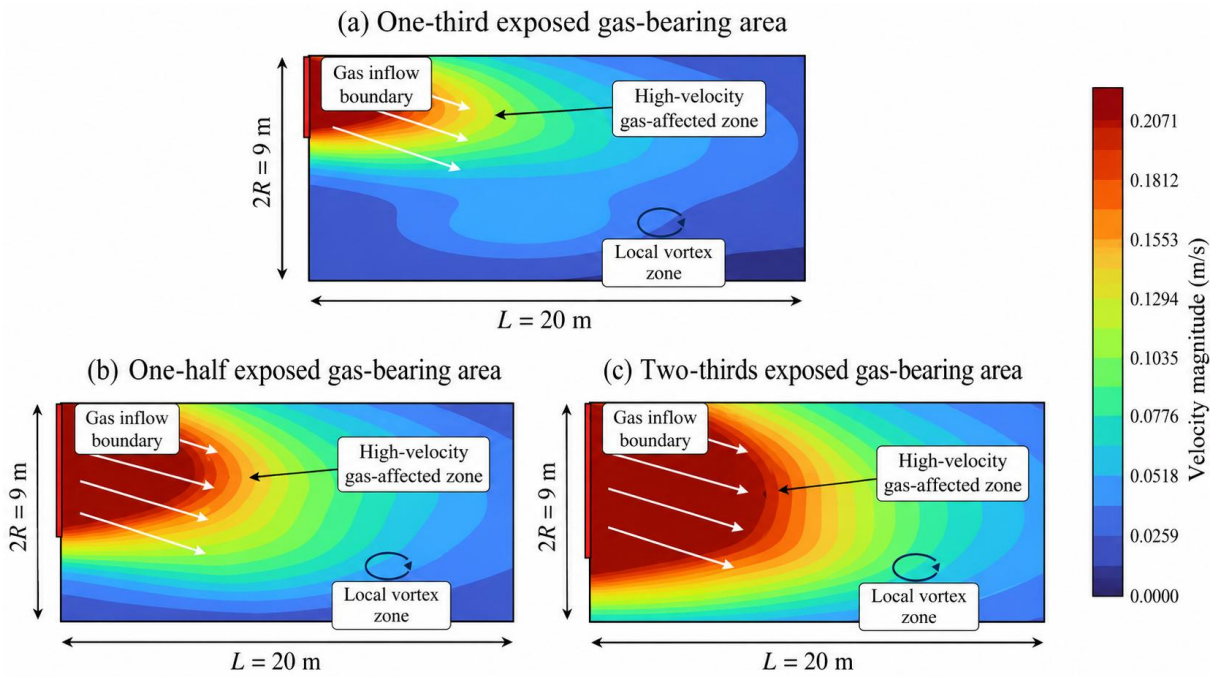


Fig. 7 Simulated gas velocity distribution for different exposed gas-bearing areas at the tunnel face: (a) one-third exposed area; (b) one-half exposed area; and (c) two-thirds exposed area.

4.1 Gas Migration Under One-third Exposed Gas-bearing Area

When the exposed gas-bearing stratum accounts for one-third of the tunnel face, gas migration shows a strongly localized pattern. The velocity field can be divided into two main regions: the directly exposed source region and the nonexposed region. In the directly exposed region, gas enters the tunnel with a relatively concentrated inflow interface and forms a high-velocity zone near the tunnel face. Along the tunnel axis, the gas velocity is highest close to the inflow boundary and gradually decreases

343 with increasing distance from the face. The velocity distribution in this region presents a triangular
344 spatial pattern, indicating that gas dispersion is mainly controlled by the local source position and the
345 axial pressure gradient.

346 In the vertical direction, when the exposed gas-bearing area is located in the upper part of the
347 tunnel face, the high-velocity region is mainly distributed in the upper tunnel space and directly in
348 front of the gas-emitting surface. The velocity increases upward in the vertical direction and decreases
349 slightly near the tunnel wall owing to the wall no-slip boundary. In contrast, the lower part of the tunnel,
350 which is not directly connected with the gas-bearing stratum, remains a low-velocity region. The sharp
351 velocity difference between the upper high-speed zone and the lower low-speed zone induces local
352 downward gas diffusion after the gas migrates a certain distance away from the face. This process leads
353 to the formation of a vortex zone in the lower part of the tunnel.

354 This result indicates that a small exposed gas-bearing area does not necessarily produce uniform
355 gas dispersion in the tunnel. Instead, gas migration is characterized by strong local concentration, clear
356 vertical zoning, and vortex formation. From the perspective of gas hazard prevention, the upper part
357 of the tunnel near the exposed gas-bearing area and the downstream low-velocity vortex zone should
358 both be regarded as potential risk regions. The former is associated with direct gas inflow, whereas the
359 latter is associated with local gas retention caused by recirculation.

360 **4.2 Gas Migration Under One-half Exposed Gas-bearing Area**

361 When the exposed gas-bearing area increases to one-half of the tunnel face, the high-velocity region
362 expands significantly compared with the one-third exposure case. The velocity is still highest near the
363 gas-emitting face and gradually decreases along the tunnel axis. However, the velocity isosurfaces

364 extend farther downward and may cross the central plane of the tunnel section. This indicates that the
365 influence of gas inflow is no longer limited to the upper tunnel space but begins to affect the middle
366 and lower parts of the cross section.

367 From the sectional velocity distribution, the proportion of low- and medium-velocity areas
368 decreases gradually along the tunnel axis. This phenomenon suggests that a larger exposed gas-bearing
369 area enhances the axial transport capacity of gas and increases the effective gas-affected space within
370 the tunnel. Nevertheless, the lower half of the tunnel still contains a local low-velocity region because
371 the inflow is not yet fully distributed over the entire tunnel face. The velocity difference between the
372 gas-influenced region and the low-speed region again produces local vortex flow.

373 Compared with the one-third exposure case, the vortex structure in the one-half exposure case
374 becomes more spatially developed. The velocity isosurface in the vortex zone shows a second-order
375 parabolic form, indicating that the recirculation region is controlled by both the expanded gas inflow
376 interface and the tunnel wall constraint. This result implies that the risk of local gas accumulation may
377 increase even if the overall gas transport capacity is enhanced. In practical construction, monitoring
378 should therefore not focus only on the direct gas-emitting surface; attention should also be paid to the
379 low-speed recirculation regions located away from the main inflow path.

380 **4.3 Gas Migration Under Two-thirds Exposed Gas-bearing Area**

381 When the exposed gas-bearing area further increases to two-thirds of the tunnel face, the gas-affected
382 region expands over a larger part of the tunnel cross section. The upper tunnel space and the region
383 directly facing the gas-emitting surface remain the main high-velocity areas. Along the axial direction,
384 gas velocity is still highest near the inflow boundary and decreases gradually with distance from the

385 tunnel face. In the vertical direction, the velocity increases upward in the directly affected region and
386 decreases slightly near the wall.

387 The most important difference from the one-third and one-half exposure cases is that the lower
388 low-velocity zone is further compressed. The velocity isosurfaces in the lower half of the tunnel show
389 a relatively simple curved form, and the velocity decreases from the upper inflow-controlled region
390 toward the lower part of the section. Although the overall affected area is larger, vortex flow can still
391 form below the gas-emitting surface. This indicates that increasing the exposed gas-bearing area does
392 not eliminate local recirculation; instead, it changes the location and spatial scale of the recirculation
393 zone.

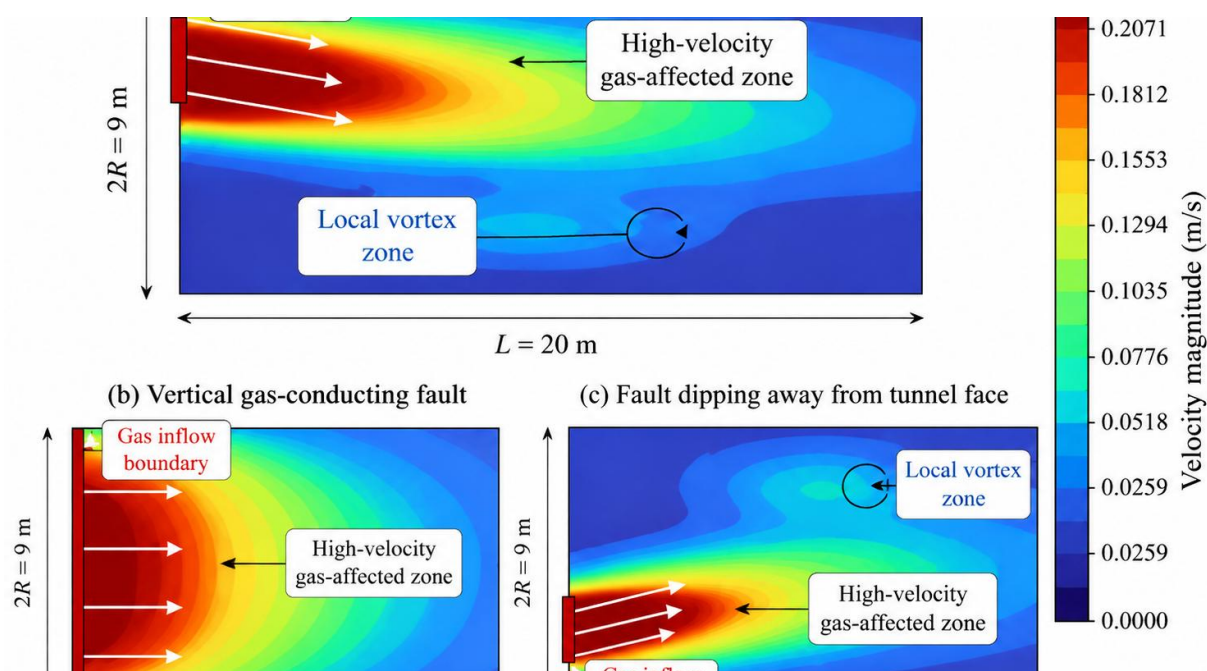
394 The comparison among the three exposed-area cases shows that the exposed gas-bearing area is
395 a key factor controlling gas migration intensity and affected range. As the exposed area increases from
396 one-third to two-thirds of the tunnel face, the gas-affected region expands downward, the proportion
397 of low-velocity space decreases, and the flow field becomes more strongly controlled by the inflow
398 boundary. However, local vortex structures remain possible in regions where velocity gradients are
399 large. Therefore, the hazard mechanism changes from localized upper-space inflow and lower-space
400 recirculation under small exposure to large-area nonuniform dispersion and residual recirculation
401 under large exposure.

402 **4.4 Influence of Gas-conducting Fault Attitude**

403 To further clarify the influence of gas-conducting structures on tunnel gas migration, three typical
404 fault-attitude cases were considered, namely a fault dipping toward the tunnel face, a vertical gas-
405 conducting fault, and a fault dipping away from the tunnel face. The corresponding gas velocity

406 distributions are shown in Fig. 8.

407



408

409 Fig. 8 Simulated gas velocity distribution for different gas-conducting fault attitudes: (a) fault

410 dipping toward the tunnel face; (b) vertical fault; and (c) fault dipping away from the tunnel face.

411

412 In addition to direct exposure of gas-bearing strata, tunnel excavation may intersect gas-
 413 conducting faults or fractured structures connected with deeper gas reservoirs. The attitude of the fault
 414 controls the contact relationship between the gas-conducting structure and the tunnel face, thereby
 415 affecting the inflow interface, velocity distribution, and local accumulation pattern.

416 When an inclined fault intersects the upper part of the tunnel face, gas enters the tunnel through
 417 a local source region. The gas velocity decreases along the tunnel axis from the inflow boundary toward
 418 the outlet. In the vertical direction, the maximum velocity occurs near the central axis of the gas-
 419 emitting region and decreases toward the surrounding area. The velocity isosurfaces exhibit a
 420 truncated-cone-like pattern, reflecting the spatial expansion of gas from a local inflow interface. When

421 the velocity decreases to a low level in the lower tunnel space, a vortex zone can form below the main
422 flow path. This condition is unfavorable because the gas source is locally concentrated and the lower
423 recirculation region may retain gas.

424 When the inclined fault intersects the lower part of the tunnel face, the overall axial attenuation
425 trend remains similar, but the location of the main inflow path changes. The high-velocity region is
426 mainly distributed in the lower or middle-lower part of the tunnel section, and the gas then expands
427 toward the upper space. As velocity decreases upward, a vortex may form in the upper part of the
428 tunnel. Because methane is lighter than air, this upper recirculation pattern deserves special attention
429 in engineering practice, as it may increase the probability of gas accumulation near the crown or upper
430 sidewall if ventilation is insufficient.

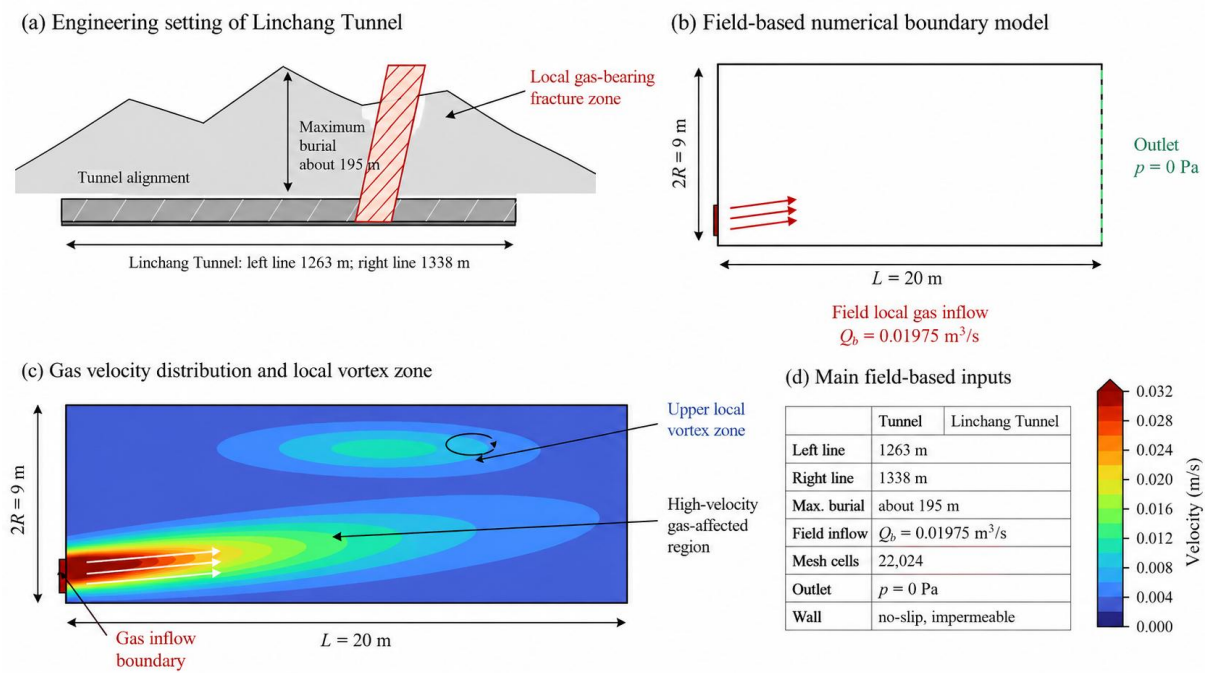
431 The vertical fault case represents a more unfavorable condition. When the fault is nearly
432 orthogonal to the excavation direction, the gas-conducting structure can intersect a larger part of the
433 tunnel face. In this case, gas inflow is no longer restricted to a local point or local band but may occur
434 over most or all of the tunnel face. Compared with inclined-fault cases, the vertical fault provides a
435 larger inflow interface and a stronger hydraulic connection between the gas source and the tunnel
436 opening. Therefore, the affected area is larger, and the possibility of rapid gas inflow is higher. This
437 explains why vertical or near-vertical gas-conducting structures should be regarded as critical targets
438 during advance geological prediction.

439 Overall, the fault attitude controls gas migration through two mechanisms. First, it determines the
440 size and position of the inflow interface at the tunnel face. Second, it controls whether gas enters the
441 tunnel as a local jet-like inflow or as a broad face-scale inflow. Inclined faults tend to produce localized
442 gas entry and asymmetric vortex structures, whereas vertical faults tend to produce a larger inflow area

443 and more extensive gas dispersion. Therefore, the risk level of a gas-conducting structure should be
 444 evaluated not only by its permeability and gas pressure but also by its spatial attitude relative to the
 445 tunnel axis.

446 **4.5 Field Evidence From Linchang Tunnel**

447 To examine whether the numerical findings are consistent with field observations, Linchang Tunnel
 448 was selected as a representative engineering case. A field-based gas dispersion model was established
 449 by considering a local gas inflow source near the lower part of the tunnel section. The outlet was
 450 assigned a static pressure boundary, and the tunnel wall was treated as a no-slip and impermeable
 451 boundary. The engineering setting, local gas inflow boundary, velocity distribution, and main
 452 simulation inputs are shown in Fig. 9.



453
 454 **Fig. 9** Field-based numerical model for gas migration analysis in Linchang Tunnel: (a) engineering
 455 setting; (b) numerical boundary model; (c) simulated gas velocity distribution; and (d) main field-
 456 based input parameters.

457 The numerical results are consistent with field observations and engineering simulation of
458 Linchang Tunnel. In the field-based model, gas inflow was assigned to a local region in the lower-right
459 part of the tunnel face, corresponding to an asymmetric gas-emitting source. The gas entered the tunnel
460 from the local inflow section and migrated mainly along the central direction of the emitting section.
461 The flow velocity decreased with increasing distance from the inflow boundary, and vortex flow
462 formed in the upper part of the tunnel.

463 This field-based pattern supports the numerical conclusion that gas migration in non-coal-
464 measure tunnels is highly sensitive to local source position. Even when the gas source is located in a
465 lower local region, the resulting flow field may generate secondary circulation in the upper space of
466 the tunnel. Therefore, the dangerous region is not necessarily limited to the immediate gas-emitting
467 point. Instead, the potential accumulation region may be located downstream or above the main inflow
468 path.

469 Field monitoring also showed that gas inflow at different sections may fluctuate with time, but
470 the fluctuation range is not always large when the surrounding rock structure and lithology remain
471 relatively uniform. This indicates that temporal variation in gas inflow is closely related to the spatial
472 variation of the surrounding rock, gas-bearing structures, and excavation disturbance. For non-coal-
473 measure tunnels, this feature means that short-term monitoring data should be interpreted together with
474 geological information. A stable gas monitoring value does not necessarily indicate the absence of risk
475 ahead of the face; it may only reflect the current lithological section.

476 The monitored CH₄ concentration data from Linchang Tunnel were further analyzed to verify the
477 spatially nonuniform gas occurrence indicated by the numerical results. The monitoring locations and
478 measured concentration results are shown in Fig. 10.

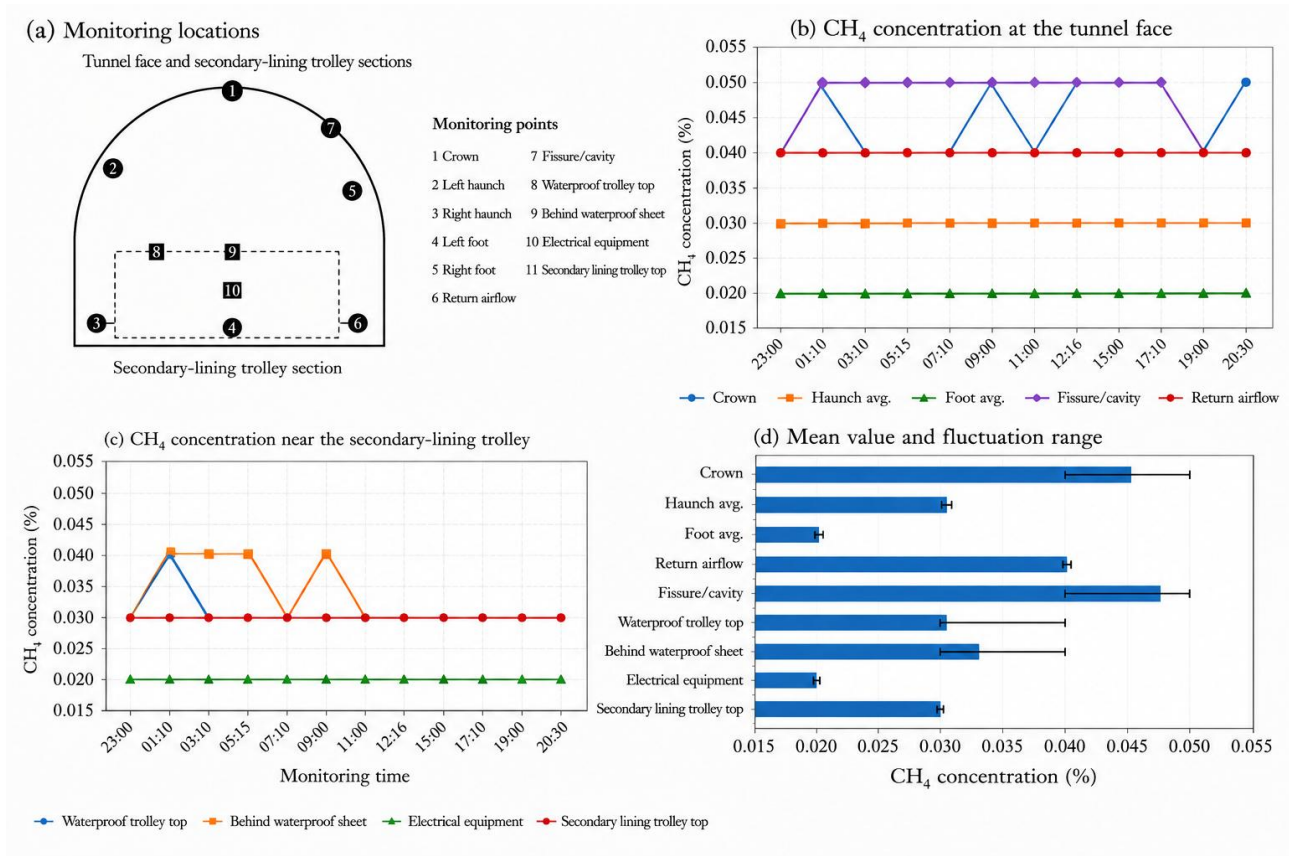


Fig. 10 Field monitoring results of gas concentration in Linchang Tunnel: (a) monitoring locations; (b) CH₄ concentration at the tunnel face; (c) CH₄ concentration near the secondary-lining trolley; and (d) mean value and fluctuation range of CH₄ concentration at different monitoring points.

4.6 Mechanism of Localized Gas Accumulation

The above results reveal a source-pathway-opening mechanism for localized gas accumulation in non-coal-measure highway tunnels. The gas source may be a hydrocarbon-generating stratum, a local gas pocket, or a deeper gas reservoir. The migration pathway may be a fracture, filled fracture, fault, or fractured structural zone. The tunnel face provides an excavation-induced low-pressure opening. When these three elements become connected, gas migrates rapidly toward the tunnel.

The spatial distribution of gas after entering the tunnel is controlled by the size and position of the exposed gas source. A small exposed area produces a localized high-velocity jet and a strong

491 velocity gradient, which can induce vortex flow in the nonexposed region. A larger exposed area
492 expands the gas-affected region but does not necessarily remove the recirculation zone. Gas-
493 conducting faults further complicate the flow field by changing the inflow interface from a local zone
494 to a larger face-scale zone. In particular, vertical faults may create a more extensive connection
495 between deep gas sources and the tunnel face.

496 From a fluid-mechanical perspective, localized accumulation is mainly caused by three effects.
497 The first is inflow localization, which creates a concentrated high-velocity region near the gas source.
498 The second is wall constraint, which reduces velocity near the tunnel boundary and promotes flow
499 separation. The third is velocity-gradient-induced recirculation, which forms vortex zones in low-
500 speed regions adjacent to the main gas flow path. These mechanisms explain why non-coal-measure
501 gas tunnels may exhibit local gas accumulation even when the total gas inflow is not extremely high.

502 Therefore, the key risk of non-coal-measure gas tunnels is not only the magnitude of gas inflow
503 but also the spatial nonuniformity of gas migration. Localized source exposure, asymmetric inflow,
504 and fault-controlled gas entry can all produce complex flow fields and local recirculation zones. These
505 zones should be considered critical targets for gas monitoring, ventilation design, and grouting control.

506 As summarized in Fig. 4, localized gas accumulation is not controlled by gas source alone, but
507 by the sequential connection among source localization, gas-conducting pathways, excavation-induced
508 opening, and velocity-gradient-induced recirculation.

509 **5 Engineering Implications for Gas Prevention**

510 **5.1 Advance Identification of Gas Sources and Gas-conducting Structures**

511 The results indicate that gas hazards in non-coal-measure tunnels are controlled by the connection
512 among gas sources, migration pathways, and excavation openings. Therefore, advance geological
513 prediction should focus not only on identifying coal-bearing strata but also on detecting carbonaceous
514 lithological units, fractured zones, water- and gas-conducting faults, and local gas-bearing structures.
515 For tunnels in the western Sichuan Plateau, carbonaceous slate, carbonaceous phyllite, fractured
516 metamorphic sandstone, and fault-related structural zones should be regarded as important geological
517 targets.

518 Advance probe drilling should be used to confirm abnormal gas pressure, gas concentration, and
519 gas flow rate ahead of the face. When local gas-bearing strata or gas-conducting structures are detected,
520 the tunnel section should be classified according to the potential exposure area, fault attitude, gas
521 pressure, and expected inflow intensity. This classification can provide the basis for determining
522 whether normal ventilation is sufficient or whether drainage and sealing measures are required.

523 **5.2 Monitoring Strategy for Nonuniform Gas Migration**

524 The numerical results show that the gas accumulation region may not coincide with the inflow source.
525 For example, gas entering from an upper local source may induce lower vortex zones, whereas gas
526 entering from a lower local source may generate upper recirculation regions. Therefore, gas sensors
527 should not be arranged only near the tunnel face or suspected inflow point. Monitoring points should
528 also cover the crown, sidewall, lower recirculation zone, and downstream sections along the main
529 airflow direction.

530 For non-coal-measure gas tunnels, the monitoring strategy should account for three spatial zones:
531 the direct inflow zone near the exposed gas source, the transition zone where the high-velocity flow
532 begins to diffuse, and the recirculation zone where local gas retention may occur. In addition, real-time
533 monitoring results should be interpreted together with excavation footage, lithological changes, probe-
534 drilling data, and structural information. This integrated interpretation is necessary because gas inflow
535 may change suddenly when the excavation intersects a new gas-bearing structure.

536 **5.3 Ventilation, Drainage, and Grouting Control**

537 Ventilation remains the basic measure for reducing gas concentration in the tunnel. However, the
538 results of this study indicate that ventilation design should consider local recirculation zones caused
539 by asymmetric gas inflow. If the ventilation flow does not effectively disturb the vortex region, gas
540 may remain locally accumulated even when the average tunnel concentration is within the allowable
541 range. Therefore, local airflow adjustment or auxiliary ventilation may be required for sections with
542 strong asymmetric inflow.

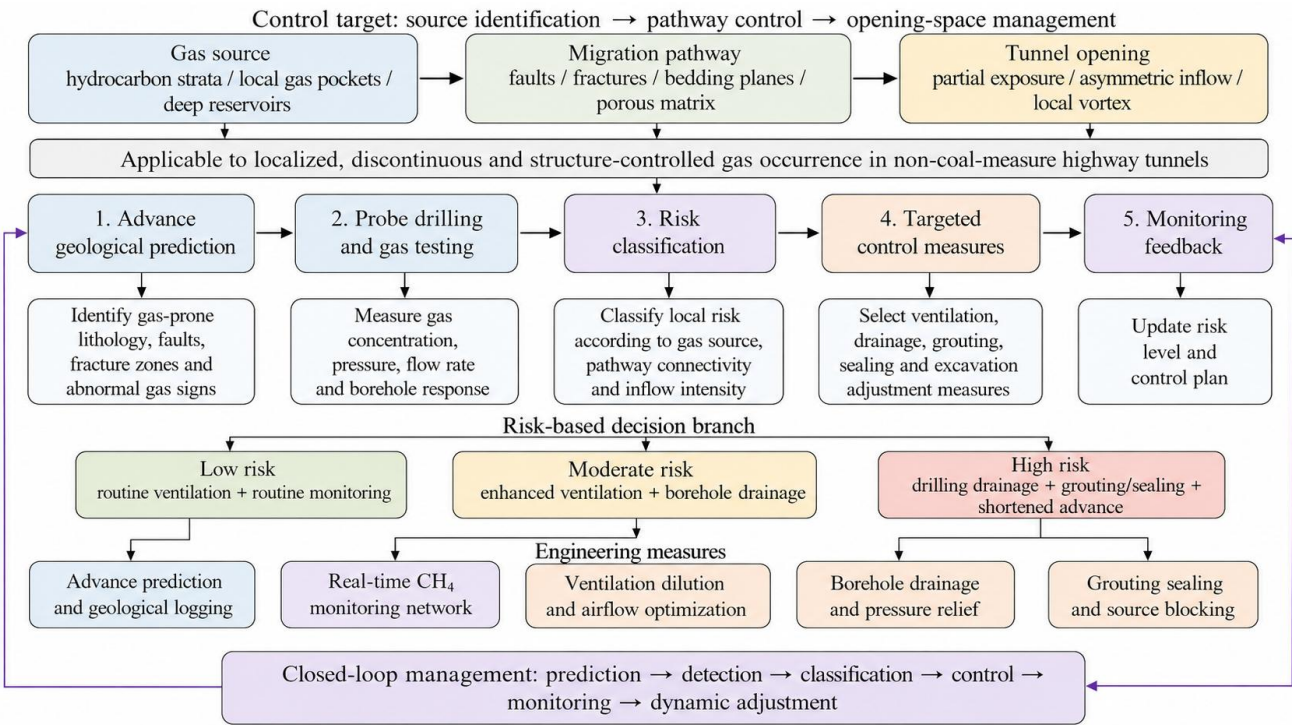
543 When advance drilling indicates gas-rich strata or gas-conducting faults, borehole drainage
544 should be adopted before excavation reaches the risk zone. Drainage can reduce gas pressure and
545 weaken the pressure gradient between the gas source and the tunnel opening. For gas-conducting faults
546 or highly fractured zones, drainage should be combined with grouting sealing when the gas pathway
547 cannot be effectively depressurized. Grouting can reduce fracture permeability, block the gas migration
548 pathway, and prevent gas inflow after excavation exposure.

549 For vertical or near-vertical gas-conducting structures, a higher control level should be adopted
550 because such structures may produce a larger inflow interface at the tunnel face. In these cases, advance

551 drainage, local sealing, and strengthened ventilation should be implemented together. The construction
 552 procedure should also be adjusted when necessary, including reducing the excavation footage,
 553 increasing monitoring frequency, and maintaining a longer observation time after each excavation
 554 cycle.

555 **5.4 Proposed Prevention Framework**

556 Based on the source-pathway-opening mechanism, numerical simulation results, and field monitoring
 557 evidence, a prevention framework for non-coal-measure gas tunnels is proposed in Fig. 11. The
 558 framework follows a closed-loop procedure involving advance geological prediction, probe drilling
 559 and gas testing, risk classification, targeted control measures, and monitoring feedback. This procedure
 560 is intended to support dynamic adjustment of ventilation, drainage, grouting, sealing, and excavation
 561 strategies during tunnel construction.



562
 563 Fig. 11 Risk-oriented prevention and control framework for gas hazards in non-coal-measure
 564 highway tunnels.

565 The risk-oriented prevention and control measures corresponding to different gas-risk conditions
566 are further summarized in Table 4.

567 Table 4 Risk-oriented prevention and control measures for non-coal-measure gas tunnels.

Risk condition	Main identification basis	Key monitoring target	Recommended control measures	Expected control effect
Low-risk section	No obvious gas-bearing strata or gas-conducting structures are detected; gas concentration remains low and stable	Tunnel face, return airflow, and routine monitoring points	Routine ventilation, regular CH ₄ monitoring, and geological logging	Maintain gas concentration within the allowable range and identify possible changes in advance
	Local hydrocarbon-generating strata, carbonaceous lithology, or gas-bearing fractured rock is exposed at the tunnel face or sidewall	Exposed gas source, tunnel crown, sidewall, and downstream low-velocity region	Enhanced ventilation, local monitoring densification, shortened excavation footage, and auxiliary airflow adjustment	Reduce local gas concentration and prevent accumulation in recirculation zones
Gas-conducting fault or fractured zone	Faults, fracture zones, bedding planes, or structural belts connected with gas-bearing zones are detected ahead of the face	Fault-exposure area, borehole gas flow rate, gas pressure, and downstream airflow region	Advance probe drilling, borehole drainage, pressure relief, strengthened ventilation, and continuous CH ₄ monitoring	Reduce gas pressure and weaken the pressure gradient between the gas source and tunnel opening
Vertical or near-vertical gas-conducting structure	The gas-conducting structure intersects a large part of the tunnel face and may form a broad inflow interface	Whole tunnel face, crown, return airflow, and secondary recirculation zones	Combined drainage, grouting sealing, ventilation optimization, reduced excavation advance, and extended observation time	Control large-area gas inflow and reduce the risk of sudden gas concentration increase
Persistent or abnormal gas inflow after drainage	Gas concentration, gas pressure, or borehole flow rate remains high after drainage	Drainage boreholes, surrounding fractures, tunnel face, and return airflow	Grouting sealing, pathway blocking, additional drainage holes, and dynamic adjustment of ventilation	Block or weaken gas migration pathways and prevent continuous gas inflow

568

569 First, geological prediction should identify potential gas sources and gas-conducting structures

570 ahead of the tunnel face. Second, gas parameter testing and monitoring should be used to evaluate gas

571 pressure, gas flow rate, and concentration variation. Third, numerical or empirical assessment should

572 be conducted for sections where local source exposure or gas-conducting faults are expected. Fourth,

573 ventilation, borehole drainage, and grouting sealing should be selected according to the risk level.

574 Finally, the prevention scheme should be dynamically updated based on field monitoring feedback.

575 This framework emphasizes that gas prevention in non-coal-measure tunnels should be source-
576 oriented and structure-oriented. The main control target is not a continuous coal seam but the local
577 connection between gas-bearing bodies, gas-conducting structures, and the excavation opening. This
578 distinction is essential for highway tunnels in high-altitude mountainous regions where non-coal-
579 measure gas hazards are spatially random and difficult to predict.

580 According to the mechanism shown in Fig. 4, gas prevention in non-coal-measure tunnels should
581 target three key links: source identification, pathway blocking or depressurization, and airflow control
582 near the tunnel opening.

583 **6 Conclusions**

584 This study investigated gas occurrence and migration mechanisms in fractured non-coal-measure
585 geological media by integrating geological investigation, field monitoring, and three-dimensional
586 numerical modelling. Based on representative tunnel cases in the western Sichuan Plateau, the
587 geological controls and migration characteristics of gas were systematically analyzed. The main
588 conclusions are summarized as follows:

589 (1) Gas occurrence in non-coal-measure fractured strata is controlled by the coupled effects of
590 gas sources, geological pathways, and excavation-induced openings. Based on field geological
591 observations, three typical gas occurrence patterns were identified, including direct exposure of gas-
592 bearing strata, structural connection between deep gas sources and underground openings, and indirect
593 migration through secondary geological pathways. These patterns demonstrate that gas occurrence in

594 non-coal-measure environments is mainly governed by the spatial relationship between gas sources
595 and fractured geological structures rather than by uniformly distributed gas-bearing layers.

596 (2) A geological source–pathway–opening framework was established to describe gas migration
597 processes in fractured geological media. The framework emphasizes the sequential interaction among
598 gas accumulation zones, fracture-controlled migration pathways, and excavation-induced openings.
599 Geological discontinuities such as faults and fractures provide preferential channels for gas transport,
600 while excavation disturbance modifies the local stress and pressure conditions, promoting gas
601 migration toward underground openings.

602 (3) Numerical simulations revealed that the spatial distribution of gas is strongly influenced by
603 exposed gas-bearing areas and gas-conducting structures. Enlarged exposed gas-bearing regions
604 increase the effective gas release area and enhance local gas accumulation, whereas interconnected
605 structural pathways accelerate gas transport by improving migration connectivity. These results
606 indicate that geological structure characteristics are critical parameters for evaluating gas migration
607 behavior in fractured non-coal-measure strata.

608 (4) Field monitoring results confirmed the reliability of the proposed gas migration mechanism
609 and numerical analysis. The observed gas concentration variations showed clear spatial and temporal
610 heterogeneity, consistent with the characteristics of localized gas sources and structurally controlled
611 migration pathways. The findings provide new insights into fracture-controlled gas transport in
612 complex geological media and contribute to the understanding of subsurface fluid migration
613 mechanisms in deep underground environments.

614 **Data Availability**

615 All data presented in this manuscript are accurate and have not been manipulated or falsified in
616 any way. The authors take full responsibility for the integrity of the data and the accuracy of their
617 presentation.

618 **Author contributions**

619 The study conception and design were contributed to by all authors. Specific tasks, including
620 conceptualization, methodology, software, validation, formal analysis, writing-original draft,
621 writing-review and editing, material preparation, data collection, and analysis, were carried out by
622 [Tong Lu], [Wenxi Fu], [Fei Ye] and [Zhanyou Luo]. Supervision, project administration, funding
623 administration, and writing-review and editing were undertaken by [Hongkai Dong], [Fei Ye], [Tong
624 Lu], and [Qing Lü]. The first draft of the manuscript was prepared by [Tong Lu], after which all authors
625 provided comments on earlier versions. Final approval of the manuscript was given by all authors.

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631 **Declarations**

632 **Conflict of interest:** The authors declare that they have no known competing financial interests
633 or personal relationships that could have appeared to influence the work reported in this paper.

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