Influence of gas migration on permeability of soft coalbed methane reservoirs under true triaxial stress conditions

Gang Wang, Zhiyuan Liu, Yanwei Hu, Cheng Fan, Wenrui Wang and Jinzhou Li

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Review form: Reviewer 1

Is the manuscript scientifically sound in its present form?
No

Are the interpretations and conclusions justified by the results?
No

Is the language acceptable?
No

Do you have any ethical concerns with this paper?
No

Have you any concerns about statistical analyses in this paper?
Yes
Recommendation?
Major revision is needed (please make suggestions in comments)

Comments to the Author(s)
A number of experimental measurements have been undertaken on Coal samples looking at the impact of gas sorption and changes in permeability related to strain. The changes in strain and the permeability changes are then modelled using a combination of rock mechanics deformation models, a sorption model and a permeability model. The paper is well presented.

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Review form: Reviewer 2

Is the manuscript scientifically sound in its present form?
Yes

Are the interpretations and conclusions justified by the results?
Yes
Is the language acceptable?  
Yes

Do you have any ethical concerns with this paper?  
No

Have you any concerns about statistical analyses in this paper?  
No

Recommendation?  
Accept with minor revision (please list in comments)

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Decision letter (RSOS-190892.R0)

07-Aug-2019

Dear Dr Wang,

The editors assigned to your paper ("Influence of Gas Migration on Permeability of Soft Coalbed Methane Reservoirs under True Triaxial Stress Conditions") have now received comments from reviewers. We would like you to revise your paper in accordance with the referee and Associate Editor suggestions which can be found below (not including confidential reports to the Editor). Please note this decision does not guarantee eventual acceptance.

Please submit a copy of your revised paper before 30-Aug-2019. Please note that the revision deadline will expire at 00.00am on this date. If we do not hear from you within this time then it will be assumed that the paper has been withdrawn. In exceptional circumstances, extensions may be possible if agreed with the Editorial Office in advance. We do not allow multiple rounds of revision so we urge you to make every effort to fully address all of the comments at this stage. If deemed necessary by the Editors, your manuscript will be sent back to one or more of the original reviewers for assessment. If the original reviewers are not available, we may invite new reviewers.

To revise your manuscript, log into http://mc.manuscriptcentral.com/rsos and enter your Author Centre, where you will find your manuscript title listed under "Manuscripts with
Decisions." Under "Actions," click on "Create a Revision." Your manuscript number has been appended to denote a revision. Revise your manuscript and upload a new version through your Author Centre.

When submitting your revised manuscript, you must respond to the comments made by the referees and upload a file "Response to Referees" in "Section 6 - File Upload". Please use this to document how you have responded to the comments, and the adjustments you have made. In order to expedite the processing of the revised manuscript, please be as specific as possible in your response.

In addition to addressing all of the reviewers' and editor's comments please also ensure that your revised manuscript contains the following sections as appropriate before the reference list:

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If your study uses humans or animals please include details of the ethical approval received, including the name of the committee that granted approval. For human studies please also detail whether informed consent was obtained. For field studies on animals please include details of all permissions, licences and/or approvals granted to carry out the fieldwork.

• Data accessibility
It is a condition of publication that all supporting data are made available either as supplementary information or preferably in a suitable permanent repository. The data accessibility section should state where the article's supporting data can be accessed. This section should also include details, where possible of where to access other relevant research materials such as statistical tools, protocols, software etc can be accessed. If the data have been deposited in an external repository this section should list the database, accession number and link to the DOI for all data from the article that have been made publicly available. Data sets that have been deposited in an external repository and have a DOI should also be appropriately cited in the manuscript and included in the reference list.

If you wish to submit your supporting data or code to Dryad (http://datadryad.org/), or modify your current submission to dryad, please use the following link: http://datadryad.org/submit?journalID=RSOS&manu=RSOS-190892

• Competing interests
Please declare any financial or non-financial competing interests, or state that you have no competing interests.

• Authors’ contributions
All submissions, other than those with a single author, must include an Authors’ Contributions section which individually lists the specific contribution of each author. The list of Authors should meet all of the following criteria; 1) substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; 2) drafting the article or revising it critically for important intellectual content; and 3) final approval of the version to be published.

All contributors who do not meet all of these criteria should be included in the acknowledgements.

We suggest the following format:
AB carried out the molecular lab work, participated in data analysis, carried out sequence alignments, participated in the design of the study and drafted the manuscript; CD carried out the statistical analyses; EF collected field data; GH conceived of the study, designed the study,
coordinated the study and helped draft the manuscript. All authors gave final approval for publication.

- Acknowledgements
  Please acknowledge anyone who contributed to the study but did not meet the authorship criteria.

- Funding statement
  Please list the source of funding for each author.

Once again, thank you for submitting your manuscript to Royal Society Open Science and I look forward to receiving your revision. If you have any questions at all, please do not hesitate to get in touch.

Kind regards,

Lianne Parkhouse
Editorial Coordinator
Royal Society Open Science
openscience@royalsociety.org

on behalf of Professor Rachel Wood (Associate Editor) and R. Kerry Rowe (Subject Editor)
openscience@royalsociety.org

Comments to Author:

Reviewers' Comments to Author:

Reviewer: 1
Comments to the Author(s)

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Author's Response to Decision Letter for (RSOS-190892.R0)

See Appendices A & B.

Decision letter (RSOS-190892.R1)

10-Sep-2019

Dear Dr Wang,

I am pleased to inform you that your manuscript entitled "Influence of Gas Migration on Permeability of Soft Coalbed Methane Reservoirs under True Triaxial Stress Conditions" is now accepted for publication in Royal Society Open Science.

You can expect to receive a proof of your article in the near future. Please contact the editorial office (openscience_proofs@royalsociety.org and openscience@royalsociety.org) to let us know if you are likely to be away from e-mail contact -- if you are going to be away, please nominate a co-author (if available) to manage the proofing process, and ensure they are copied into your email to the journal.

Due to rapid publication and an extremely tight schedule, if comments are not received, your paper may experience a delay in publication.

Royal Society Open Science operates under a continuous publication model (http://bit.ly/cpFAQ). Your article will be published straight into the next open issue and this will be the final version of the paper. As such, it can be cited immediately by other researchers. As the issue version of your paper will be the only version to be published I would advise you to check your proofs thoroughly as changes cannot be made once the paper is published.

On behalf of the Editors of Royal Society Open Science, we look forward to your continued contributions to the Journal.

Kind regards,
Andrew Dunn
Royal Society Open Science Editorial Office
Royal Society Open Science
openscience@royalsociety.org

on behalf of Professor Rachel Wood (Associate Editor) and R. Kerry Rowe (Subject Editor)
openscience@royalsociety.org

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# Appendix A

## ROYAL SOCIETY OPEN SCIENCE

**Influence of Gas Migration on Permeability of Soft Coalbed Methane Reservoirs under True Triaxial Stress Conditions**

| Journal            | Royal Society Open Science |
|--------------------|-----------------------------|
| Manuscript ID      | RSOS-190892                 |
| Article Type       | Research                    |
| Date Submitted by the Author | 01-Jun-2019               |
| Complete List of Authors: | Wang, Gang; Shandong University of Science and Technology, College of Mining and Safety Engineering |
|                     | liu, zhiyuan; Shandong University of Science and Technology, College of Mining and Safety Engineering |
|                     | hu, yanwei; Shandong University of Science and Technology, College of Mining and Safety Engineering |
|                     | fan, cheng; Shandong University of Science and Technology, College of Mining and Safety Engineering |
|                     | wang, wenrui; Shandong University of Science and Technology, College of Mining and Safety Engineering |
|                     | li, jinzhou; Shandong University of Science and Technology, College of Mining and Safety Engineering |
| Subject:            | Energy < ENGINEERING AND TECHNOLOGY, Engineering geology < ENGINEERING AND TECHNOLOGY |
| Keywords:           | True triaxial stress, Soft coalbed, Gas migration, Permeability model |
| Subject Category:   | Engineering                 |

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Statement (if applicable):
CUST_IF_YES_ETHICS :No data available.

Data

It is a condition of publication that data, code and materials supporting your paper are made publicly available. Does your paper present new data?:
Yes

Statement (if applicable):
The datasets supporting this article have been uploaded as part of the electronic supplementary material.

Conflict of interest

I/We declare we have no competing interests

Statement (if applicable):
CUST_STATE_CONFLICT :No data available.

Authors’ contributions

This paper has multiple authors and our individual contributions were as below

Statement (if applicable):
W.R.W. and J.Z.L. conceived and designed the experiments and theoretical models; Y.W.H. and F.C. performed the experiments; G.W. and Z.Y.L. interpreted the results and wrote the manuscript.
All authors gave final approval for publication.
Influence of Gas Migration on Permeability of Soft Coalbed Methane Reservoirs under True Triaxial Stress Conditions

Gang Wang a,b, Zhiyuan Liu b, Yanwei Hu b, Wenrui Wang b, Jinzhou Li b

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b Shandong University of Science and Technology, College of Mining and Safety Engineering, Qingdao 266590, China

Abstract: The permeability of coal body is the key parameter restricting the efficient extraction of coalbed methane, and scholars have analyzed it from two angles of the change of stress state and porosity of coal body. However, there is still a lack of study on the mechanism of gas migration and movement in soft coalbed methane reservoir under the coupling between the true triaxial stress field (maximum principal stress $\sigma_1 >$ intermediate principal stress $\sigma_2 >$ minimum principal stress $\sigma_3$) and the gas pressure field. In this paper, the coal gas adsorption and seepage experiments are conducted through the self-developed true triaxial "gas-solid" coupled coal mass seepage system with gas as the adsorption and seepage medium and coal briquette taking the place of soft coalbed methane reservoirs. Furthermore, the coal gas adsorption deformation model and the permeability evolution model taking gas adsorption into account are developed. Through analysis of both experimental and theoretic results, main conclusions are drawn as follows: (1) With the increase of gas pressure, the adsorption deformation variation of coal mass is divided into a slow growth zone, a stable growth zone and a rapid growth zone. (2) The gas adsorption deformation model developed can predict the variation trend of coal mass adsorption volumetric strains for different types of soft coalbeds, and the fitting variance of experimental and theoretical volumetric strains is above 98%. (3) With the increase of maximum principal stress difference, the coal permeability variation curve shows 2 obvious turning points, which can be divided into a slow reduction zone, a rapid reduction zone and a steady reduction zone. (4) The permeability model of coal mass considering the gas adsorption effect can reflect the variation characteristics of permeability in the rapid reduction zone, and the overall fitting variance of experimental and theoretical permeabilities is above 91%. The above results could provide a reliable experimental and theoretical basis for improving coalbed methane extraction rates.

Key words: True triaxial stress, Soft coalbed, Gas migration, Permeability model
1 Introduction

During coal seam mining process, coal mass in front of working faces is usually affected by mining disturbances and thus subject to unequal stresses in three directions. To be specific, the support pressure in the vertical direction increases and the pressure in the horizontal directions is relieved. As a consequence, expansion deformation of coal mass (Wang and Pang, 2017), and further continuous development, expansion and penetration of pores and fracture structures in coal mass occur, finally leading to desorption, permeability enhancement and migration of gas in pores (Xie et al., 2013). Especially in the presence of soft coalbeds, pore fracture development and gas migration become more severe, which have a dynamic influence on the stable extraction of coalbed methane. Therefore, understanding the mechanism of deformation damage and permeability evolution of soft coal mass under the coupling of gas and stress is essential to increase coalbed methane extraction rates (Pan and Connell, 2012) and realize scientific coal mining (Qian et al., 2018).

Many researchers have studied the adsorption of coalbed methane and the permeability of coal and rock mass through physical experiments. Meng and Li, (2017) and Connell et al. (2016) studied the effect of gas adsorption on coal matrix and cleat deformation. In addition, some researchers focused on the permeability characteristics of coal mass and conducted a large number of physical experiments (Geng et al., 2017; Pan et al., 2018; Liu et al., 2018; Mitra et al., 2012; Yin et al., 2015). A few researchers investigated the permeation law of shale and sandstone under true triaxial stress conditions (Sato et al., 2018; Li et al., 2016). However, most of them put their main efforts in the experimental analysis of mechanical properties of coal under quasi-triaxial stresses, which could not reflect the actual stress state of coalbed methane reservoirs. Moreover, there is a lack of deep research on the mechanism behind the experimental phenomena.

In order to provide theoretical support for physical experiments, Palmer I. and Mansoori J. (1998) examined the relationship between permeability and porosity of coalbed methane reservoirs under simple stress conditions. Shi and Durucan (2004) developed a dynamic evolution model for the permeability of coalbed methane reservoirs taking into account the influence of effective stresses on the adsorption deformation and permeability of coal mass. Liu et al. (2011) studied the effect of coalbed methane adsorption strain on coal permeability. Zang and Wang (2017) proposed a model based on quasi-steady-state diffusion to reflect the relationship between gas adsorption deformation
and permeability evolution.

A number of investigators explored the impact of coalbed methane adsorption on coal deformation and permeability under conventional triaxial stress conditions by combining physical experiments with theoretical derivation. Peng et al. (2017) quantitatively described the degree of influence of coal pore expansion deformation and matrix deformation on permeability of coal mass by means of the strain splitting function. Wei et al. (2017) and Peng et al. (2014) built a bi-directional permeability model considering the relationship between effective stresses and pore pressure. Liu et al. (2017) introduced an internal expansion coefficient (f) to quantify the effect of coal mass matrix deformation caused by gas adsorption on coal pore diameter and permeability. Lu and Connell (2016), Wang et al. (2017) and Connell (2016) improved the effective stress principle reflecting the influence of coal mass deformation, gas diffusion in coal matrix and gas migration in fractures on coal mass permeability with pore pressure, matrix pressure and gas adsorption pressure considered for the double porosity characteristics of coalbed methane reservoirs. Saurabh and Harpalani (2018) suggested a coal permeability model of coal mass suitable for elastic and inelastic deformation of coal mass, but only the effect of stress was considered. Lu et al. (2016) explored the effect of effective stresses and matrix adsorption deformation on coal permeability and developed a coal mass permeability model under specific boundary conditions.

Researchers above have studied the influence of coalbed methane adsorption deformation and coal porosity on coal permeability. However, the following insufficiencies exist: (1) owing to the limitations of test equipment, it is impossible to fully reflect the variation of permeability of coalbed methane reservoirs under real stress conditions, especially for soft coalbeds; (2) the theoretical models of coal permeability developed have not considered coalbed methane adsorption.

The soft coal seam is the key reservoir to prevent coal and gas outburst and improve the pumping rate of coalbed methane. Therefore, this paper is focused on the mechanical properties and seepage characteristics of soft coalbeds, which are carried out through the self-developed true triaxial "gas-solid" coupled coal mass seepage system with gas as the adsorption and seepage medium and coal briquette taking the place of soft coalbed methane reservoirs. Moreover, the coal permeability continuity model considering the adsorption of coalbed methane is proposed. In addition, the deformation and permeability characteristics exhibited in the experiment and the theoretical model are
compared and analyzed, and the mechanism of gas migration in soft coalbed methane reservoirs is further understood. This could provide a theoretical support and experimental basis for efficient coalbed methane extraction.

2 Adsorption and seepage experiment for soft coal mass under true triaxial stress conditions

2.1 Experimental system

The self-developed true three-axis "gas-solid" coupled coal mass seepage experimental system is used for this experiment (Wang et al., 2018). As shown in Figure 1, it is divided into 4 parts: a true triaxial pressure chamber, a hydraulic servo system, a gas seepage system and a data monitoring and control system. The true triaxial pressure chamber is the place for the gas adsorption and seepage experiment. The hydraulic servo system is the power source of true triaxial stresses. The gas seepage system is mainly composed of a pressure relief valve and a gas cylinder. The data monitoring system has a variety of high-precision sensors and data acquisition devices, which can monitor and collect the instantaneous deformation and gas flow information in real time. This apparatus has a feature of "two rigid and one soft, tri-directional independent loading”, which means that $\sigma_1$ and $\sigma_2$ of coal mass are rigid stresses, and $\sigma_3$ is a flexible stress (owing to hydraulic oil). Therefore, this apparatus can be used to conduct gas adsorption and seepage experiments under a variety of complex loading and unloading stress conditions.
2.2 Preparation of soft coal samples

The raw coal for this experiment is taken from the 8# anthracite coal seam of Yuyang Coal Mine of Chongqing Songzao Coal and Electricity Co., Ltd. This coal seam has soft and brittle coal, and many coal and gas outburst accidents happened in working faces at different mining depths there. The specific industrial indicators for the 8# coal seam are as follows: volatile content 9.87-10.97%, ash content 11.53-19.13%, water content 0.56-2.55%, true density 1.5-1.53 $\text{g/cm}^3$, apparent density 1.34-1.38 $\text{g/cm}^3$, firmness coefficient 0.21–0.38, uniaxial compressive strength 0.89 MPa, and coal mass failure type Class III-V (Wang et al., 2016).

The 8# anthracite coal seam is a soft coal seam. According to the experimental requirements for the sample size (100 mm × 100 mm × 200 mm), the raw coal is not suitable for this experiment because it is difficult to form and the raw coal pore fractures are randomly distributed. However, coal briquette has a similar variation trend in mechanical properties and permeability characteristics to that of raw coal (Espinoza et al., 2016) and it has good homogeneity suitable for repetitive experiments (Geng et al., 2017). Therefore, the briquette samples are used for this experiment. According to "GB/T 23561.9-2009 Methods for determining the physical and mechanical properties of coal and rock", the
coal mass is processed into rectangular soft coal samples of 100 mm × 100 mm × 200 mm. After the basic mechanical test on these coal samples, 4 kinds of soft coal samples are selected for the gas adsorption deformation and permeability experiment with their basic parameters shown in Table 1.

### Table 1 Basic parameters of 4 kinds of coal samples

| Basic parameter                        | Symbol and unit | Coal Sample 1 | Coal Sample 2 | Coal Sample 3 | Coal Sample 4 |
|----------------------------------------|-----------------|--------------|--------------|--------------|--------------|
| Pore bulk modulus                      | $K_p$ (GMPa)    | 31.45        | 26.50        | 17.10        | 31.50        |
| Initial porosity                       | $\varphi$ (%)   | 3.7          | 4.6          | 4.1          | 5.0          |
| Bulk modulus of porous medium          | $K_s$ (GMPa)    | 850          | 570          | 420          | 630          |
| Young’s modulus                        | $E_s$ (GMPa)    | 990          | 760          | 400          | 680          |
| Poisson’s ratio                         | $\nu_s$         | 0.30         | 0.28         | 0.26         | 0.32         |
| Density                                | $\rho_s$ (g/cm$^3$) | 1.25       | 1.22         | 1.24         | 1.21         |
| Pore diameter to diameter ratio        | $c$             | 0.1          |              |              |              |
| Langmuir volume                        | $V_L$ (cm$^3$/g) |              | 17.7 (CH$_4$) |              |              |
| Langmuir pressure                      | $P_L$ (MPa)     |              |              | 7.2 (CH$_4$) |              |
| Volumetric strain coefficient          | $\varepsilon_g$ (g/cm$^3$) |              |              |              | 7.4 × 10$^{-4}$ |

#### 2.3 Experimental method and procedure

Two types of experiments are conducted: a constant stress experiment and a constant gas adsorption pressure experiment. In the gas adsorption deformation experiment, the external stress is kept constant, and in the coal mass seepage experiment, the gas pressure is kept constant. For the experimental procedure, the experiment under an initial true triaxial stress condition of 4 MPa for $\sigma_3$, 6 MPa for $\sigma_2$ and 8 MPa for $\sigma_1$ and an initial adsorption pressure of 1 MPa for $P$ is introduced as an example, as shown in Figure 2.

Before the experiment begins, the overall system air tightness check is performed. When the reading of the gas flow accumulator is unchanged and the relation curve between gas flow and time tends to be horizontal, it is indicated that the air tightness is good. Now the experiment can be carried out.

1. Gas adsorption experiment of coal mass under true triaxial stress conditions: First, increase $\sigma_1$, $\sigma_2$, $\sigma_3$ gradually to a predetermined hydrostatic pressure of 4 MPa at a speed of 0.01 MPa/s. Next, keep
constant, and increase $\sigma_1$, $\sigma_2$ to 6 MPa. Then, increase $\sigma_1$ to 8 MPa. Now a true triaxial stress environment is formed. After the stress environment is stable, open the high-pressure cylinder valve to adjust the inlet pressure to 1 MPa, and then close the inlet and outlet valves of the gas pipeline. Finally, carry out the gas adsorption deformation experiment. When the adsorption deformation curve of the coal sample tends to be horizontal, which indicates that the coal sample adsorption deformation is saturated, the amount of coal sample adsorption deformation is continued to be measured with the increase of the coal sample adsorption pressure at an interval of 0.2 MPa.

(2) Gas seepage experiment of coal mass under true triaxial stress conditions: After the initial true triaxial stress environment of 4 MPa for $\sigma_3$, 6 MPa for $\sigma_2$ and 8 MPa for $\sigma_1$ is formed based on the above steps, open the high-pressure cylinder valve slowly to adjust the inlet pressure to 1 MPa, so that the gas can enter the coal sample slowly. After the relation curve between gas flow and time tends to be horizontal, which means that the seepage is in the stable state, increase $\sigma_1$ gradually from 8 MPa at an interval of 1 MPa until the end of the experiment, during which the gas pressure is kept constant.

Figure 2 Schematic diagram of experimental method and procedure

3 Test results and analysis

3.1 Effect of gas adsorption on deformation of soft coal mass

Figure 3 shows the forms of 4 kinds of coal samples after the gas adsorption experiments. From the appearance of the coal samples, no obvious difference in their deformation forms are found. Figure 4-7 shows the deformation curves of the coal samples caused by gas adsorption and measured under true triaxial stress conditions. When the external stress is kept constant, the gas adsorption pressure increases from 0 to 8 MPa in increments of 0.2 MPa. As the gas adsorption pressure increases, the strains ($\varepsilon_1, \varepsilon_2, \varepsilon_3$) of the 4 kinds of coal samples in the $\sigma_1$, $\sigma_2$ and $\sigma_3$ directions increase gradually, and the
volumetric strain ($\varepsilon_v$) also increases gradually. However, for each kind of coal sample, $\varepsilon_v$ is the maximum, followed by $\varepsilon_1$ and then $\varepsilon_3$, and $\varepsilon_2$ is the minimum, i.e., $\varepsilon_v > \varepsilon_1 > \varepsilon_3 > \varepsilon_2$.

![Figure 3 Forms of coal samples after gas adsorption experiments](image1)

![Figure 4 Deformation characteristics of Coal Sample 1 under different gas adsorption pressures](image2)

![Figure 5 Deformation characteristics of Coal Sample 2 under different gas adsorption pressures](image3)
Figure 6 Deformation characteristics of Coal Sample 3 under different gas adsorption pressures

Figure 7 Deformation characteristics of Coal Sample 4 under different gas adsorption pressures

From Figure 4-7, it can be seen that the deformation variation of coal mass exhibits different deformation rates under different gas adsorption pressures, and that it can be divided into a slow growth zone, a stable growth zone and a rapid growth zone. For the slow growth zone, when the gas adsorption pressure is lower than about 1 MPa, the strains in all three directions and volumetric strains of the coal samples change slightly. For example, the volumetric strain increases by 0.00084 for Coal Sample 1, by 0.00128 for Coal Sample 2, by 0.00079 for Coal Sample 3, and by 0.00198 for Coal Sample 4 (shown in Table 2). The strains in the three directions are different. For the stable growth zone, when the gas pressure reaches about 5 MPa, the deformation of the coal samples is relatively stable, and the deformation in all three directions and volumetric strains show significant differences. For the rapid growth zone, when the gas pressure reaches the maximum value, the deformation in all
three directions and volumetric strains of the coal samples are in a rapid growth stage.

| Sample Growth zone                  | Coal Sample 1 | Coal Sample 2 | Coal Sample 3 | Coal Sample 4 |
|-------------------------------------|--------------|--------------|--------------|--------------|
| Slow growth zone                    | 0.00084      | 0.00128      | 0.00079      | 0.00198      |
| Stable growth zone                  | 0.01044      | 0.0142       | 0.01628      | 0.02721      |
| Rapid growth zone                   | 0.02255      | 0.02652      | 0.02601      | 0.05529      |

From a microscopic point of view, the coal samples undergo expansion deformation after adsorbing gas. When the gas adsorption occurs, the gas molecules adhere to the surface of coal particles, resulting in a decrease in the surface tension of the coal particles. This means the attraction between the molecules on the surface of coal particles and the molecules inside is reduced and thus the distance between them is increased. Therefore, the coal mass after its gas adsorption is more likely to be deformed than before its gas adsorption (Li et al., 2018).

From a macroscopic point of view, the coal samples in this experiment are cuboids, and their length in the $\sigma_1$ direction is twice of those in the other two directions. Consequently, the adsorption deformation mainly occurs in the $\sigma_1$ direction. For the other two directions, rigid loading is adopted in the $\sigma_2$ direction with a large stress, and flexible loading is adopted in the $\sigma_3$ direction with a small stress. This indicates that the external binding force in the $\sigma_2$ direction is larger than that in the $\sigma_3$ direction, and thus deformation is prone to occur in the $\sigma_3$ direction. Therefore, the gas adsorption deformation exhibits the characteristics of $\varepsilon_1 > \varepsilon_3 > \varepsilon_2$.

In this gas adsorption experiment, gas pressure is the main factor of coal mass deformation. Gas pressure acts as both adsorption pressure and pore pressure in coal sample pore fractures. Specifically, the effect of gas adsorption plays a leading role under low gas pressure conditions while the effect of pore pressure plays a dominant role under high gas pressure conditions.

When the external stress of the coal mass is constant and the gas adsorption pressure is less than 5 MPa, the volumetric strains of the coal samples depend on the gas adsorption of the coal samples. Moreover, gas adsorption is related to gas pressure. As gas pressure increases, gas adsorption becomes stronger, and more gas is adsorbed on the pore surface of the coal samples resulting in a larger adsorption thickness. Consequently, the transfer resistance between gas molecules increases. When the gas pressure is low, the pore pressure is small, and thus it is difficult to cause the deformation of coal.
mass. Therefore, the volumetric strains of the coal samples in this zone are mainly determined by gas adsorption.

When the gas adsorption pressure is greater than 5 MPa, the gas pressure exhibits the effect of pore pressure other than the effect of adsorption, and the interior of the coal samples expand outward owing to pore pressure. This indicates that the volumetric strains of the coal samples increase with the increase of the gas pressure. The larger the gas pressure, the larger the pore pressure, and the greater the volumetric strain increase. In this process, gas adsorption is reduced to a secondary position.

3.2 Mechanism of gas adsorption deformation

In this paper, the emphatical density, Poisson's ratio, Young's modulus, bulk modulus, pore structure length, diameter and other parameters of soft coalbed methane reservoirs are adopted to model the coalbed methane reservoir medium (Yaodong et al., 2007). In this model, the soft coalbed methane reservoir and gas satisfy the following conditions: (1) the reservoir is an isotropic continuous medium, which means that the physical and mechanical properties are the same in all directions; (2) the reservoir is a saturated mixture composed of coal matrix skeleton and gas that is free and adsorbed in pore structures; (3) the coal matrix is always in a solid state, and the adsorbed gas is always in a gaseous state, and the two will not transform into each other; (4) the temperature of gas in reservoirs is kept constant during the adsorption and desorption process.

Gas in soft coalbed reservoirs mainly exists in an absorbed state, and the volume deformation of coal mass is caused by both pore pressure and gas adsorption. Schere (1986) believed that when gas-containing coal is assumed to be an isotropic elastic medium and the elasticity energy is equal to the change of surface energy, the expansion strain caused by gas adsorption is:

\[
e_s = \gamma A \rho_s \frac{f(\varphi, \nu_s)}{E_s} \tag{1}
\]

\[
f(\varphi, \nu_s) = \left[1 - \frac{4c\varphi(1-2\nu_s)}{3-5\nu_s}\right] \frac{2(1-\nu_s)-c\varphi(1+\nu_s)}{2-3c\varphi} \tag{1-1}
\]

\[
c = \frac{8\sqrt{2}}{3\pi} ; \quad \varphi = \frac{a}{l} \tag{1-2}
\]

where \(e_s\) is the adsorption volumetric strain, \(\gamma\) is the surface potential energy, \(A\) is the specific surface area, \(\rho_s\) is the density, \(E_s\) is Young's modulus, \(\nu_s\) is Poisson's ratio, \(a\) is the pore radius, \(l\) is the pore
length.

Using the Langmuir adsorption model, Pan and Connell (2007) obtained the relationship of surface potential energy with specific surface area and Langmuir adsorption constant with the help of the analysis of adsorption effects (Myers, 2002):

$$\gamma = \left[ \int_0^p v^d dp - RTP_L \ln(1 + V_L P) \right] / A$$  \hspace{1cm} (2)

With Equation (1) and Equation (2) combined, the relationship of the adsorption volumetric strain of coalbed methane with reservoir density, Young’s modulus, Poisson’s ratio, etc. is further simplified (Zhu et al., 2009):

$$\varepsilon_v = \rho_s f \left( \varphi_s, V_s \right) \left[ \int_0^p v^d dp - RTP_L \ln(1 + V_L P) \right]$$  \hspace{1cm} (3)

where $v_s$ is the volume of adsorbed gas, $P$ is the pressure of adsorbed gas, $R$ is the gas constant, $T$ is the temperature, and $V_L$ and $P_L$ are the Langmuir constants.

Cui and Bustin (2005) pointed out that the volumetric deformation of coal mass caused by gas adsorption is linear with the gas adsorption pressure:

$$\varepsilon_v = \varepsilon_g \cdot V_a$$  \hspace{1cm} (4)

$$v_a = \frac{V_L P}{P + P_L}$$  \hspace{1cm} (4-1)

where $\varepsilon_g$ is the adsorption volumetric strain coefficient.

When the temperature of the physical experiment environment is constant, the influence of temperature on gas adsorption is not considered, and thus the reservoir strain $\varepsilon_v$ caused by gas adsorption is:

$$\varepsilon_v = \left( 1 - \frac{4\varphi(1 - 2v)}{3 - 5v} \right) \left( \frac{2(1 - v) - c\varphi(1 + v)}{2 - 3\varphi} \right) \frac{\rho_s}{E_s} \int_0^p \varepsilon_g P \frac{v}{P + P_L} dp$$  \hspace{1cm} (5)

After variable transformation and integration, Equation (5) is simplified:

$$\varepsilon_v = \frac{V_L \rho_s \varepsilon_g f \left( \varphi_s, V_s \right)}{E_s} \left[ P - P_L \ln(P + P_L) \right]$$  \hspace{1cm} (6)

According to the gas adsorption deformation model described above, the adsorption deformation of a coalbed methane reservoir is affected by its own density, Poisson's ratio, Young’s modulus, porosity, adsorbed gas pressure, etc. in a constant temperature physical experiment environment. After
the corresponding values of the basic mechanical parameters of the coal samples in Table 1 are put into Equation (6), the theoretical curve of the gas adsorption deformation with the gas pressure is obtained, as shown in Figure 8-11.

Figure 8 Relationship between volumetric strain and gas adsorption pressure for Coal Sample 1

Figure 9 Relationship between volumetric strain and gas adsorption pressure for Coal Sample 2
Figure 10 Relationship between volumetric strain and gas adsorption pressure for Coal Sample 3

Figure 11 Relationship between volumetric strain and gas adsorption pressure for Coal Sample 4

Figure 8-11 shows the comparison of experimental and theoretical variation of the coal sample volumetric strain with the gas adsorption pressure. From the fitting curve of the modeled volumetric strain and the experimental volumetric strain for coal samples, it can be seen that the volumetric strain of coal samples increases gradually with the increase of the gas adsorption pressure. The fitting variances of the experimental and the theoretical results for the 4 kinds of coal samples are all above 98%, which indicates that the experimental results are very close to the theoretical results.

When the gas adsorption pressure is below Point A (2.5 MPa), the experimental volumetric strain of the coal samples is less than the theoretical volumetric strain. When the gas adsorption pressure is above Point B (about 5 MPa), the experimental volumetric strain is greater than the theoretical volume strain.
volumetric strain. When the gas adsorption pressure is between Point A and Point B (2-5 MPa), the experimental adsorption volumetric strain of the coal samples almost coincides with the theoretical adsorption volumetric strain curve.

The mechanism of influence of gas migration on deformation of coal mass is analyzed in combination with the gas adsorption deformation model (Equation (6)). The gas in pores and fractures of coal mass is mainly in two states, an adsorbed state and a free state, and most of it is in an adsorbed state. The gas molecules are adsorbed on the pore surface and release adsorption energy causing coal mass to undergo expansion deformation. As the gas pressure increases, more gas molecules are adsorbed on the surface of coal, and more adsorption heat is released, finally resulting in larger expansion deformation. However, the amount of free gas in pores also increases substantially at the same time and formed an increasing pore pressure, which could result in deformation and failure of coal mass in the form of volumetric stress (Wu and Zhao, 2005). Therefore, when the gas pressure is large, the experimental volumetric strain results of coal mass are higher than the corresponding theoretical results. The reason is that when the gas pressure is increased to a certain extent, resulting in obvious macroscopic deformation of coal mass, the mechanical effect of gas adsorption on coal matrix and pore fracture structure is not obvious.

Furthermore, the fitting of the experimental results is performed. It is found that the fitting variance of the experimental and theoretical gas adsorption volumetric strain is above 98%, indicating that the model developed in this paper can predict the volumetric strain variation of coal samples under different gas pressure conditions.

### 3.3 Influence of true triaxial stresses on permeability of soft coal mass

The permeability of the coal samples can be calculated from the gas pressure and flow rate measured in the experiment, and the equation for the calculation is (Wang et al., 2018):

\[
K = \frac{2q\mu L P_n}{A(P_2^2 - P_1^2)}
\]

(7)

where \(K\) is the permeability, m²; \(q\) is the gas permeation velocity of coal mass, m³/s (\(q = D \times C_k\), \(D\) is the reading displayed on the flow accumulator, \(C_k\) is the flowmeter coefficient, which is 0.719 for CH₄); \(\mu\) is the gas dynamic viscosity coefficient (1.10×10⁻¹¹ MPa·s for CH₄); \(L\) is the length of the sample, m; \(P_n\) is 0.1 MPa; \(A\) is the cross-sectional area, m²; \(P_1\) is the outlet gas pressure, MPa; \(P_2\) is the inlet gas...
pressure, MPa.

Table 3 Parameters of permeability experiments for coal samples

| Basic parameters                  | Symbols and units | Coal Sample 1 | Coal Sample 2 | Coal Sample 3 | Coal Sample 4 |
|-----------------------------------|-------------------|---------------|---------------|---------------|---------------|
| CH₄ adsorption pressure           | P (MPa)           | 4             | 4             | 3             | 3             |
| Minimum principal stress          | σ₃ (MPa)          | 5             | 4.8           | 3.7           | 3.5           |
| Intermediate principal stress     | σ₂ (MPa)          | 7.5           | 7.2           | 5.6           | 5.3           |
| Adsorption volumetric strain      | εᵥ                | 0.008         | 0.0126        | 0.0070        | 0.0204        |

In order to further study the relationship between coal permeability and stress, the differences in adsorption deformation and permeability of coal samples under different gas pressures are considered. According to the basic parameters of the 4 kinds of coal samples, the volumetric strains measured in the gas adsorption deformation experiment, and the theoretical model parameters of gas adsorption deformation, the parameters of the coal mass permeability experiment under true triaxial stress conditions are determined, as shown in Table 3.
Figure 13 Variation of permeability with principle stress difference for 4 kinds of coal samples

Figure 12 shows the forms of the 4 kinds of coal samples after the coal seepage experiment. In the coal seepage experiment under true triaxial stress conditions, the coal samples are mainly affected by shear stress, and obvious macroscopic fractures are formed on the surface of coal samples. The main fractures have a horizontal angle of about 65° (green dotted line), and flaky shedding pits are formed on the surface of the coal samples (yellow dotted line). Figure 13 shows the permeability variation curve of the 4 kinds of coal samples under true triaxial stress conditions. As the maximum principal stress difference (Δσ) increases under true triaxial stress conditions, the permeability of coal samples decreases gradually in different stages, and these stages are indicated by different zones: a slow reduction zone, a rapid reduction zone, and a steady reduction zone.

For the slow reduction zone, with the increase of Δσ from 2 MPa to about 4.5 MPa, the permeability of the 4 kinds of coal samples decreases to varying degrees. Specifically, it decreases by 0.79×10^{-15} m^2 for Coal Sample 1, by 0.77×10^{-15} m^2 for Coal Sample 2, by 0.43×10^{-15} m^2 for Coal Sample 3, and by 0.71×10^{-15} m^2 for Coal Sample 4, as shown in Table 4. The permeability decreases slowly because the original pores of coal samples are continuously compressed, resulting in narrowed the seepage channels.

For the rapid reduction zone, as Δσ increases from 4.5 MPa to about 12 MPa, the permeability continues to decrease rapidly and approximately linearly, and the coal samples undergo elastic deformation. Now the coal samples enter the elastic stage and they are in a state of compression deformation. If the pressure relief measures are taken, the coal samples deformed can be restored to their original state. However, the original pores and fractures of coal samples continue to be compressed, the permeability continues to decrease rapidly.

For the steady reduction zone, as Δσ increases from about 12 MPa to 18 MPa, the coal samples are subjected to large true triaxial stresses. This leads to a transition of coal samples from a compressed state to an expanded state. New micro fractures are generated owing to the relative slip between the internal particles of the coal samples, finally resulting in macro fractures. However, the closure of the original fractures counteracts the generation of new fractures, causing the permeability of coal samples to decrease slowly. If σ1 continues to be increased at this time, the coal samples are destructed after
they reach their peak strength. As a consequence, the permeability of coal samples exhibits an upward trend.

### Table 4 Variation of permeability difference for coal samples

| Permeability                        | Coal sample 1 | Coal sample 2 | Coal sample 3 | Coal sample 4 |
|------------------------------------|---------------|---------------|---------------|---------------|
| Initial permeability×10^{-15} m²   | 6.38          | 7.21          | 6.52          | 5.27          |
| Slow reduction zone - permeability difference×10^{-15} m² | 0.79          | 0.77          | 0.43          | 0.71          |
| Rapid reduction zone - permeability difference×10^{-15} m² | 3.72          | 4.77          | 4.92          | 3.81          |
| Steady reduction zone - permeability difference×10^{-15} m² | 0.36          | 0.33          | 0.16          | 0.03          |

### 3.4 Evolution mechanism of permeability for soft coal mass

Chikatamarla et al. (2004) found through gas adsorption experiments that the volumetric strain of coal induced by gas adsorption is proportional to the amount of gas adsorbed. According to rock mechanics, the stress and strain of coal deformation can be expressed as (Palciauskas and Domenico, 1982):

\[
\sigma_y = \frac{E_s}{1 + \nu_s} (\varepsilon_y + \frac{v_s}{1 - 2\nu_s} \varepsilon_v \delta_y) + \zeta p \delta_y + K_s \varepsilon_v \delta_y
\]

\[
K_s = \frac{E_s}{3(1 - 2\nu_s)}
\]

where \( \varepsilon_v \) is the volumetric strain of coal; \( E_s \) is Young's modulus; \( K_s \) is the bulk modulus; \( \zeta \) is the biot coefficient with a range of 0-1; \( \delta \) is the Kronecker delta function (when \( i=j, \delta_{ij}=1 \); when \( i \neq j, \delta_{ij}=0 \)).

The area in front of the mining face of coalbed methane reservoirs is divided into a plastic zone, an elastoplastic zone, an elastic zone and a primary rock stress zone. Coal mass is under the three-dimensional stresses composed of vertical stress \( \sigma_z \) (\( \sigma_1 \)), lateral stress \( \sigma_y \) (\( \sigma_2 \)) and horizontal stress \( \sigma_x \) (\( \sigma_3 \)). With \( \varepsilon_3 = 0 \) assumed, Equation (8) combined, and the gas adsorption deformation model (Equation (6)) considered, the numerical relationship between the initial three-dimensional
stresses $\sigma_3, \sigma_2, \sigma_1$ can be obtained:

$$\sigma_3 = \frac{v_s}{1-v_s} \sigma_1 + \frac{1-2v_s}{1-v_s} \left[ P + \rho_s f \left( \phi, v_s \right) \int_{P_s}^{P} \frac{V_s}{P+P_z} dp \right]$$  \hspace{1cm} (9)$$

$$\varepsilon_1 = \frac{\sigma_1}{E_S}, \quad \sigma_1 = \sigma_a, \quad \sigma_2 = \left( 1 + \eta \right) \sigma_3$$  \hspace{1cm} (9-1)$$

where $\sigma_a$ is the uniaxial compressive strength of soft reservoir coal mass, and $\eta$ is the length ratio of the standard sample of soft reservoir coal mass.

The change of the stress of reservoir coal in the vertical direction can be expressed as:

$$\sigma_1 - \sigma_1^0 = \frac{2(1-2v_s)}{3(1-v_s)} \left[ (P - P_0) + K_s \left( \varepsilon_s - \varepsilon_s^0 \right) \right]$$  \hspace{1cm} (10)$$

According to Cui and Bustin (2005) and Wang et al. (2012), the relationship between stress, gas pressure and permeability is:

$$k = k_0 \exp \left\{ -\frac{3}{K_p} \left[ \left( \sigma - \sigma_0 \right) - (P - P_0) \right] \right\}$$  \hspace{1cm} (11)$$

Then substitute Equation (7) into Equation (8):

$$k = k_0 \exp \left\{ -\frac{3}{K_p} \left[ \left( \sigma_1 - \sigma_1^0 \right) - \frac{E_s}{2(1-2v_s)} \left( \varepsilon_s - \varepsilon_s^0 \right) \right] \right\}$$  \hspace{1cm} (12)$$

where $K_p$ is the pore bulk modulus ($K_p = K_s \cdot \phi$), $(\sigma_1 - \sigma_1^0)$ is the difference ($\Delta \sigma$) between $\sigma_1$ and the initial maximum principal stress ($\sigma_1^0$).

The gas adsorption volumetric strain difference ($\varepsilon_s - \varepsilon_s^0$) can be solved by Equation (6), and thus the theoretical model for the permeability of coal mass changing with $\Delta \sigma$ under true triaxial stress conditions is obtained:

$$k = k_0 \exp \left\{ -\frac{3}{K_p} \left[ \left( \sigma_1 - \sigma_1^+ \right) - \frac{f \left( \phi, v_s \right) V_s \rho_s E_s}{2(1-2v_s)} \left( P - P_1 \ln(P + P_1) \right) \left( \frac{P_2}{P_1} \right) \right] \right\}$$  \hspace{1cm} (13)$$

The theoretical permeability variation curve of the coal samples can be obtained by Equation (13) with the basic parameters of the coal samples in Table 3 and the initial permeability measured in the seepage experiment. And then the theoretical curve and the experimental curve are compared, as shown in Figure 14-17.
Figure 14 Variation of permeability with principal stress difference for Coal Sample 1

Figure 15 Variation of permeability with principal stress difference for Coal Sample 2

Figure 16 Variation of permeability with principal stress difference for Coal Sample 3
Figure 17 Variation of permeability with principal stress difference for Coal Sample 4

Figure 14-17 indicates that the experimental and theoretical permeability variations are consistent with the increase of $\Delta \sigma$ from 2 to 16 MPa in increments of 0.5 MPa when the gas permeation pressure difference is constant. They both show a trend of decreasing with increasing load stress, and the decrease in permeability gets slower and slower. The reason for this can be explained as follows. When the gas pressure is kept constant, the compressive stress that the coal samples are subjected to increases gradually with the increase of $\sigma_1$, leading to different degrees of closure of the internal pores and fractures of coal samples. As a result, the porosity decreases, the fracture aperture decreases, the gas flow channel narrows, and the permeability of coal samples decreases.

Based on the parameters of density, Poisson's ratio, Young's modulus, bulk modulus and initial permeability of different soft coal samples, the permeability model developed in this paper can predict the permeability of coal in the rapid reduction zone pretty well, but it is not enough to reflect the characteristics of the transition between the 3 zones. However, the overall fitting variance of the theoretical model results and the experimental results is between 91% and 97%, indicating that the coal permeability variation model has a high accuracy and a good applicability.

4 Discussion

The gas adsorption experiment and permeability experiment of coal in soft coalbed methane reservoirs under true triaxial stress conditions are carried out, and the gas adsorption deformation model and coal permeability model are proposed in this paper. These models take the mechanism of gas adsorption and migration of soft coalbed methane reservoirs into account. However, the influence
of single factors such as density, Poisson's ratio and uniaxial compressive strength on the gas adsorption and seepage of soft coalbed methane reservoirs is not quantitatively analyzed. Only the overall deformation and permeability trends of different soft coal samples are examined. After the analysis of the adsorption deformation of the 4 kinds of coal samples, it is indicated in Figure 4-7 that the strains of Coal Sample 4 are smaller than those of the other 3 coal samples while the Poisson's ratio and porosity of Coal Sample 4 are larger than those of the other 3 coal samples. In addition, the other parameters such as density, Young's modulus, bulk modulus of all 4 coal samples are similar. Therefore, the reason of the small adsorption deformation of the coal samples might be the large Poisson's ratio and porosity of the coal samples. In the future, the orthogonal adsorption-seepage experiments on the different mechanical parameters of the coal samples involved in this paper will be carried out systematically in order to further analyze the applicable range of the coal permeability model with gas adsorption taken into account.

5 Conclusion

In this paper, the influence of gas adsorption and migration on the deformation and permeability of soft coal mass under true triaxial stress conditions is explored through the self-developed true triaxial "gas-solid" coupled coal mass seepage experimental system. Furthermore, the gas adsorption deformation model and permeability model of coal mass are developed. In addition, the mechanism behind the gas adsorption-seepage experimental phenomenon is investigated. From all the analysis, the following main conclusions are drawn:

(1) In the coal mass adsorption and seepage experiment under true triaxial stress conditions, the gas adsorption deformation variation of soft coal mass with the increase of gas pressure is divided into a slow growth zone, a stable growth zone and a rapid growth zone. The permeability variation is divided into a slow reduction zone, a rapid reduction zone and a steady reduction zone with 2 obvious turning points as the principle stress difference increases.

(2) The deformation characteristics of the soft reservoir coal during the gas adsorption experiment under true triaxial stress conditions are analyzed theoretically and the gas adsorption deformation model is developed. This model can predict the dynamic evolution trend of the adsorption deformation of soft coal samples under different gas adsorption pressures because the fitting variance of the theoretical and experimental results is above 98%.
(3) Through the gas adsorption deformation model and the permeability experiment of the coal samples under true triaxial stress conditions, the relationship between the gas adsorption deformation and permeability of the soft coal samples is further analyzed, and the permeability evolution model of coal mass considering the gas adsorption is developed. It is found that the fitting variance of the theoretical and experimental permeabilities is above 91%, and that this model can predict the variation trend of coal mass permeability in the rapid reduction zone.

**Ethics.** This article does not present research with ethical considerations.

**Data accessibility.** The datasets supporting this article have been uploaded as part of the electronic supplementary material.

**Authors’ contributions.** W.R.W. and J.Z.L. conceived and designed the experiments and theoretical models; Y.W.H. and F.C. performed the experiments; G.W. and Z.Y.L. interpreted the results and wrote the manuscript.

All authors gave final approval for publication.

**Competing interests.** We declare we have no competing interests.

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Dear Editor,

On behalf of my co-authors, I am submitting the enclosed manuscript “Influence of Gas Migration on Permeability of Soft Coalbed Methane Reservoirs under True Triaxial Stress Conditions” for possible publication in ROYAL SOCIETY OPEN SCIENCE.

We certify that we have participated sufficiently in the work to take public responsibility for the appropriateness of the experimental design and method, and the collection, analysis, and interpretation of the data.

We have reviewed the final version of the manuscript and approve it for publication. The manuscript has not been published in whole or in part nor is it being considered for publication elsewhere.

Yours Sincerely,

Author: Gang Wang a, b, *, Zhiyuan Liu b, Yanwei Hu b, Cheng Fan b, Wenrui Wang b, Jinzhou Li b
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We deeply appreciate your consideration of our manuscript, and we look forward to receiving comments from the reviewers. If you have any queries, please do not hesitate to contact me at the address below.

Thank you and best regards.

Yours sincerely,

Gang Wang

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**Highlights:**

1. Under true triaxial stress conditions, the gas adsorption and seepage experiments of soft coal mass is carried out, and the obtained permeability curve exhibits 2 obvious turning points.

2. The adsorption deformation law of soft coal body under the coupling of true triaxial stress field and gas pressure field is studied, which conforms to the established gas adsorption deformation model.

3. The permeability model of soft coal body considering gas adsorption is established, and the evolution mechanism of soft coal body permeability under the condition of true triaxial stress is revealed.
Appendix B

Manuscript Number: RSOS-190892.R1

Title: Influence of Gas Migration on Permeability of Soft Coalbed Methane Reservoirs under True Triaxial Stress Conditions

Dear Editor and Reviewers,

Thank you for your comments on our manuscript entitled “Influence of Gas Migration on Permeability of Soft Coalbed Methane Reservoirs under True Triaxial Stress Conditions” (Manuscript Number: RSOS-190892.R1). These comments are all valuable and very helpful for revising and improving our paper, as well as the important guiding significance to our researches. We have studied the comments carefully and have made corrections, which we hope to meet with approval. Revised portions are marked in red in the manuscript. The main corrections in the paper and the responses to the reviewers’ comments are as follows.

Looking forward to hearing from you.

Sincerely yours,

Gang Wang
Reviewer: 1

Comments to the Author(s)

1. A number of experimental measurements have been undertaken on Coal samples looking at the impact of gas sorption and changes in permeability related to strain. The changes in strain and the permeability changes are then modelled using a combination of rock mechanics deformation models, a sorption model and a permeability model. The paper is well presented.

As there is only a "yes // no" option to a number of the questions I have been asked, I have been forced to choose the "no" option, where in most cases it is close to being acceptable. However there are a number of key issues which need to be clarified or revisited. I have attached a commented manuscript which will aid the authors in reviewing their paper.

Response: Thank you for your recognition and valuable comments on this article. For your question, we have explained accordingly. In order to facilitate your review, the revised part has been highlighted in red.

2. A key issue is that the authors identify a "slow", "stable" and "Rapid" sample growth zone, based on the relationship to an elastic model describing the relationship between gas pressure and sample strain. However there is no clear inclusion of the triaxial state of pressure in this model, and it appears that a formulation is used that uses a value of stress as the surface potential energy. The issue is that the division of stable to rapid is occurring when the gas pressure is significantly above two of the axial pressures. The model is not able to account for the triaxial stress, and thus I believe this is significantly influencing the results and the interpretation. I would suggest revisiting the results with this in mind, as the experimental results are certainly good quality. Also the modelling results show good correlations. However process understanding is key.

Response: First of all, thank you very much for your advice. We strongly agree with the your comment of “process understanding is the key”. The innovation of this paper is to combine the true triaxial coal body adsorption and seepage test with the theoretical model. In fact, the theoretical model of this paper considers the true triaxial stress factor, but the transformation of stress into true triaxial strain is indicated in the paper. As shown in the paper, the adsorption volumetric strain is calculated by the strain in the three stress directions. If the volumetric strain is reconverted into the three-direction
strain, the adsorption strain model is complicated. For the sake of brevity, the author has transformed the true triaxial stress.

The starting point of the model proposed by the experts is to establish the surface potential energy, and we also draw on the research results of the predecessors. For example, Vandamme et al. (2010) established a model between stress, strain, pore pressure and free energy from the perspective of energy balance. Kowalczyk et al. (2008) studied the relationship between adsorption stress and adsorption deformation from the perspective of thermodynamics. Moore (2012) reviewed the production and development of coalbed methane, pointed out the importance of coalbed methane as a clean fuel, and reported the adsorption characteristics of coal as a key factor in the study of coalbed methane utilization. With the increase of the adsorption pressure, the adsorption capacity of coalbed methane is gradually enhanced. Ottiger et al. (2008) studied the adsorption capacity of methane and carbon dioxide in coal. As the adsorption pressure increases, the amount of gas adsorbed on coal increases. Li et al. (2010) studied the adsorption characteristics of methane under high adsorption pressure conditions. Pini et al. (2010) studied the adsorption characteristics of methane, carbon dioxide, nitrogen, etc., and established an adsorption model from the perspective of thermal energy. Battistutta et al. (2010) also studied the adsorption energy of nitrogen, carbon dioxide and methane, established an adsorption model by combining the adsorption amount and temperature, and pointed out that as the adsorption time increases, the adsorption pressure of the gas becomes smaller and smaller. Karacan (2007) studied the volumetric strain caused by gas adsorption by means of scanning electron microscopy. With Monte Carlo and molecular dynamics, Zhang et al. (2014) simulated the adsorption of methane under different adsorption pressures and different coal body moisture contents. Busch and Gensterblum (2011) summarized the research status of coalbed methane adsorption deformation, and pointed out that the adsorption deformation increases with the increase of the coal machine rank, especially when the adsorption pressure is lower than 10 MPa. The detailed research status is shown in Table 1.
### Table 1 Status of research of establishing adsorption deformation model based on energy and dynamics

| No. | Title                                                                 | Research content                                                                                                                                                                                                 |
|-----|-----------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1   | Adsorption and Strain: The CO$_2$-Induced Swelling of Coal            | As long as the microstructure is well enough characterized, the volumetric strain induced by surface energy effects can therefore precisely be calculated theoretically. This calculation will be possible, however, only if the surface stress which prevails at the interface between the solid matrix and the pore fluid is known.  
\[
\varepsilon = -\frac{8\pi R^2b}{\Omega_0 \phi} \cdot \frac{\varepsilon_{\text{hom}}}{2} = -\frac{8\pi R^2b}{\Omega_0 \phi} \cdot \frac{1}{9K} 
\]  |
| 2   | Adsorption-Induced Deformation of Microporous Carbons: Pore Size Distribution Effect | An advantage of Eq. (14) is avoiding the differentiation of isotherms with respect to the pore size; however, the fluid density must be calculated quite accurately. In the current paper we determined adsorption stress from Eq. (13) by using the grand Canonical Monte Carlo simulation method.  
\[
\sigma_i(H,\mu) = k_B T \frac{\partial N_i(\mu)}{\partial H} + \int_0^\mu \frac{\partial N_i}{\partial H} \cdot \mu 
\]  |
|     |                                                                       | Example of two types of adsorption isotherm curves: high rank coal (from the Pocahontas coal seam in the Appalachian basin) and low rank coal (from the Powder River basin). Note that the high rank coal has an initial steep slope and then flattens whereas the low rank coal tends to have a steady slope. |
| 3   | Coalbed methane: A review                                             | Example of two types of adsorption isotherm curves: high rank coal (from the Pocahontas coal seam in the Appalachian basin) and low rank coal (from the Powder River basin). Note that the high rank coal has an initial steep slope and then flattens whereas the low rank coal tends to have a steady slope. |
| 4   | Combined Monte Carlo and molecular dynamics simulation of methane adsorption on dry and moist coal | Adsorbed and bulk densities of CH$_4$ on dry and moist coal as a function of pressure at 308 K.                                                                                                                |

3. Likewise the permeability model appears to be assuming no axial strain in the s2 or s3 direction, however the experimental results show strain in these directions. I have made a number
Response: Here we put forward our explanation for Comment 3 and Comment 4 together.

Equation 8 and 9 in this paper are descriptions of stress in three directions. In order to obtain the initial true triaxial stress state of the coal body, the initial true triaxial stress is calculated by the method of Zhenxiong and Peitao (2018). Combined with the test process of this true triaxial seepage test, the true triaxial stress is first generated, then the maximum principal stress is changed, and the variation law of permeability during the dynamic evolution of true triaxial stress is studied. It is not a model in which the permeability changes as the three stresses change. Therefore, the established permeability model is consistent with the true triaxial seepage process. In the meantime, the influence of adsorption deformation on permeability is considered.

Connell et al. (2010) reviewed the evolution of the permeability model under triaxial stress-strain conditions. L. D. Connell (2009) established a coupled numerical model and used the model to study the applicability of the geomechanical assumptions for coal seam gas drainage. Chen et al. (2015) studied the effects of effective stress and reservoir pressure on shale permeability, and established a permeability model related to two factors. Wu et al. (2010) pointed out that the permeability and porosity vary with the effective stress, and the adsorption-induced strain forms the overall stress and increases the effective stress. H. Zhang et al. (2008) studied the influence of coal adsorption deformation on coal porosity and permeability. The finite element model was used to quantitatively analyze the coal permeability change rate, gas flow and deformation. Siriwadane et al. (2009) studied the coal permeability of carbon dioxide under different confining pressures, pointing out that the coal permeability gradually decreased with the increase of the confining pressure. Liu et al. (2011) studied the applicability of the uniaxial strain permeability model and the multiaxial strain permeability model, pointing out that the former was more in line with the overall behavior of coalbed methane reservoirs under typical conditions, while the latter is more suitable for the permeability law under laboratory conditions. The detailed research status is shown in Table 1.

Table 2 Status of research on permeability evolution models

| No. | Title | Research content |
|-----|-------|------------------|
| 1   | An analytical coal permeability model for tri-axial strain and stress | In this section the theoretical basis for the models developed in this paper is presented. In the next section the model derivations are presented for laboratory testing with tri-axial deformation and cylindrical geometry of |
| Conditions | Coupled flow and geomechanical processes during gas production from coal seams |
|-----------|-----------------------------------------------------------------------------|
| Core samples. | Shi and Durucan (2004) derived the relationship between the coal permeability and the effective stress using the following incremental stress–strain relationships, Eq. (3), for each normal effective stress component. |
| \[k = k_0 \left( \frac{\phi}{\phi_0} \right)^3 \] \hspace{1cm} \[k = k_0 \left( 1 - \frac{1}{\phi_0} \left[ \frac{1}{k} (\bar{p}_x - \bar{p}_y) + \left( \bar{e}_x^{(3)} - \bar{e}_y^{(3)} \right) \right] \right)^2 \] \hspace{1cm} \[k = k_0 \exp \left\{ -3 \left( \frac{E}{3K} \left[ \frac{2(1 + \nu)}{3} \bar{p}_x - \frac{\alpha E}{3K} (1 - \nu) \right] \right) \right\} \] \hspace{1cm} (1); (2); (3) |
| Coupled flow and geomechanical processes during gas production from coal seams | The relationship between the coal permeability for each axis and the effective stress can be expressed by Eq. (8). |
| \[k_i = k_0 e^{-3 \kappa_k \left( \sigma_{ii}^{(3)} - \sigma_{ii}^{(0)} \right)} \] \hspace{1cm} (8) |
| Dual poroelastic response of a coal seam to CO\textsubscript{2} injection | The relation between matrix permeability ratio and matrix pore pressure at a specific point is shown in Fig. 6. The permeability ratio increases with an increase in the matrix pore pressure as expected with the effective stress dependency. In these situations, the effective stress effect and the sorption effect are competing: an increase in the matrix pressure... For these particular conditions the resultant effect is a monotonic decrease in permeability with increasing pressure as the effects of sorption-induced swelling dominate. |
| Combined Monte Carlo and molecular dynamics simulation of methane adsorption on dry and moist coal | Assuming thermal expansion/contraction and matrix swelling/shrinkage are isotropic, the stress-strain relationships for a non-isothermal coalbed may be written as (negative in compression). |
| \[\Delta \phi_{ij} = \frac{1}{2C} \Delta \sigma_{ij} - \left( \frac{1}{2C} - \frac{1}{9K} \right) \Delta \sigma_{ii} \bar{\phi}_i \] \hspace{1cm} \[\Delta \rho_{ij} \bar{\rho}_i + \frac{\alpha}{3K} \Delta \phi_0 \bar{\phi}_i + \frac{\Delta \epsilon_{ii}}{3} \bar{\phi}_i + \frac{\alpha_\tau}{3} \Delta \theta_{0i} \] |
| Combined Monte Carlo and molecular dynamics simulation of methane adsorption on dry and moist coal | The exponential relation was used for the permeability calculation: \[k = \exp \left( \frac{-3 \Delta \phi_i}{E_i} \right) = \exp \left[ - \frac{3}{E_i} \left( -\frac{\nu}{1-\nu} \Delta \rho + \frac{E}{1-\nu} \gamma \Delta S \right) \right] \] |
| Combined Monte Carlo and molecular dynamics simulation of methane adsorption on dry and moist coal | The cubic relation between porosity and permeability was used for this derivation, as shown below: |
4. The permeability model developed appears principally to be a 1D s1 approximation, which may explain the slightly less accurate fitting of the experimental results.

Response: Thank you for your valuable comments. Please see the previous explanation.

5. The results where gas pressure above a principal axis stress has been allowed need to be revisited, as there is then no real control on strain.

Response: Thanks for your advice. Our previous ideas coincide with your thoughts. We considered the gas sealing problem at that time, that is, as the adsorption deformation and the adsorption pressure increase, especially when the gas pressure exceeds the maximum principal stress, how we seal the gas so that the gas does not leak. The reason why we did not change the axial strain is we have two layers of heat-shrink tubing around the coal sample. This is found to be effective from the gas adsorption test results.

6. Although the experimental work is truly triaxial, it appears the modelling is not. This is fine as long as the limitations and best approximations are included and an understanding of what the limiting factors may be.

Response: Thank you very much for your recognition of our research work. The model in this paper may not be seen as a true triaxial model from the expression. The reason why we did this is explained in the article. Our subsequent research work is to establish a more accurate true triaxial model. The true triaxial test of this paper lays an important experimental foundation for our model derivation in future.

7. The title needs rethinking a bit as it doesn't really reflect the contents, currently emphasises the flow aspect of gas, but the work is all about gas pressures and stress conditions.

Response: Thanks for your valuable suggestion. We attach great importance to this. The title for this paper is changed. The gas migration visualization and the true triaxial model in the coal are important tasks that we will carry out later. For example, the former may be achieved by suing nuclear magnetic resonance technology and CT scanning technology. However, in this paper, the effects of gas pressure and true triaxial stress environment on gas migration in coal are mainly studied.
Reviewer: 2

Comments to the Author(s)

1. The author designed a gas adsorption and seepage test for soft coal under true triaxial stress conditions for soft coal. The stress conditions are in line with coal mining. The true three-dimensional stress state in the process, the research object and the research method are very innovative. Based on the true triaxial test, the author established a theoretical model of coal gas adsorption deformation and a model of seepage evolution. The results of the two models are similar to those exhibited by the true triaxial test. It is the verification of the accuracy of the true triaxial test and the verification of the applicability of the adsorption and seepage models. The analysis is clear and logical. Therefore, the research results of this paper are very valuable, and can provide experimental and theoretical guidance for coalbed methane extraction, and it is recommended to accept after minor revision.

Response: Thank you for your recognition and valuable comments on this article. For your question, we have explained accordingly. In order to facilitate your review, the revised part has been highlighted in red.

2. The true triaxial seepage test system of this paper is independently developed by the author. I am interested in this. I propose a design pattern of “two rigid and one soft, three-way independent loading”. Why should we design this way? What are the advantages? Can the author explain?

Response: Thank you very much for your recognition of our research work. It is mentioned in this paper to overcome the jamming problem in the three-way rigid loading process. Because in the three-direction rigid loading, the rigid indenter will generate a large frictional force against the surface of the coal sample, and the coal body cannot be released smoothly under pressure deformation, which will easily cause the indenter to get stuck and interrupt the test.

3. The manuscript text on page 2, line 34 is not used properly. The author says “the permeation law of shale”. This is not accurate. It is recommended that the author change to “Seepage Regulation of shale”.

Response: Thank you very much for your suggestion. This phrase has been revised, and highlighted in red.
4. The adsorption and percolation tests in this paper all require high sealing performance of the test equipment, and the author does not explain how the coal sample is sealed. Is it because of the length of the article? If yes, please explain here; if not, please add the reason to the body.

Response: Thank you very much for your suggestion. In fact, one of the innovations of the true triaxial gas-solid coupling coal seepage test system is the realization of gas sealing, which has been discussed in our previous article. Please refer to Wang et al. (2018).

5. The author of Figure 1 is very beautiful, but there are three other signs in the lower left corner. If it is related to the device, please mark it. If not, please delete it.

Response: Thank you very much for your suggestion. This has been revised.

6. From the author's industrial analysis of coal samples, it is known that raw coal is relatively soft and not easy to form. The author solved this problem by using coal briquettes. This method is feasible and worth promoting. But does the author consider the consistency of other mechanical properties of briquette with raw coal?

Response: Thank you for your recognition and valuable comments on the article. The authors tested the mechanical properties of both raw coal samples (listed in the paper) and finally selected briquettes samples for this test.

7. In Figure 3, the first three coal samples are the same color, and the fourth coal sample has a high exposure. Can the author be replaced by a uniform one? Is there no uniform exposure after the end of the test?

Response: Thank you very much for your suggestion. The photos were taken with a mobile phone camera after the experiment without photo retouching. We apologize for not being able to replace them.

8. It can be seen from Fig. 4-7 that when the gas adsorption pressure is lower than 1 MPa, the deformation of the coal sample in three directions is inconsistent, and the variation law is not uniform. According to the experience of reviewing experts, this stage is indeed complicated. The deformation of coal samples is dominated by stress or gas adsorption, and even the creep characteristics of coal samples. There is no unified understanding. How does the author understand the mechanism of action of gas adsorption at lower pressures?

Response: Thank you for your recognition and valuable comments on this article. The authors believe that the effect of gas adsorption and external stress on coal sample deformation is related to the
coal sample body at low pressures. If the coal sample has strong adsorption, the gas adsorption should dominant at low pressures.

9. In the manuscript, on page 10, line 22, the author points out that “the coal mass after its gas adsorption is more likely to be deformed than before its gas adsorption”. This view is correct, but for the language to be more concise, it is recommended that the author “before” Delete later.

Response: Thank you very much for your suggestion. This has been revised, and highlighted in red.

10. Similarly, on page 10, line 52, the author wants to express that the higher the adsorption pressure, the higher the amount of gas adsorbed? The authors say "and more gas is adsorbed on the pore surface of the coal samples resulting in a larger adsorption thickness." The suggestion is changed to "and more gas is adsorbed on the pore surface of the coal samples, resulting in a larger adsorption thickness."

Response: Thank you very much for your suggestion. This has been revised, and highlighted in red.

11. On page 11, page 28 of the manuscript, the three stress directions are mistake, and there are two periods at the end of the paragraph. I hope the author can check all the writing formats in the text.

Response: Thank you very much for your suggestion. This has been revised, and highlighted in red.

12. What does "model:WSXFBX1(USER)" in Figure 8 mean? The same as Figure 9-11 below, is the fitted model? Is it different from the theoretical model derived by the author?

Response: Thanks. "model:WSXFBX1(USER)" is named by the author himself, which is consistent with all the parameters of the model being derived.

13. On page 15, line 15 of the manuscript, the unit of gas flow is error.

Response: Thank you very much for your suggestion. This has been revised, and highlighted in red.

14. There is a problem with the format of Table 3.

Response: Thank you very much for your suggestion. This has been revised, and highlighted in red.

15. The format of the headings of Figures 10 and 11 is not uniform.
Response: Thank you very much for your suggestion. This has been revised, and highlighted in red.

16. From the true triaxial adsorption test in Figure 8-11, two turning points can be clearly observed, but the theoretical model curve does not show a turning point. The reason is also explained in detail in the article, but the author can correct the model parameters and make the theory Is the model better matched to the test results?

Response: Thank you very much for your suggestion. This is the law exhibited by the true triaxial test, and the theoretical model does not have these two turning points. In our subsequent research, we will focus on establishing true triaxial adsorption and seepage models. However, this is still in progress.

17. The unit of density in Table 4 is not written correctly.

Response: Thank you very much for your suggestion. This has been revised, and highlighted in red.

18. Is the true triaxial seepage test in this paper based on the previous adsorption test? Or is the two tests separate? From the author's point of view, the two tests are carried out separately, so that the coal sample failure morphology after the true triaxial gas adsorption can be obtained, and the author is established to conduct the continuity test. If it is a continuous test, is the form of coal sample adsorption deformation obtained in a separate study of gas adsorption?

Response: Thank you very much for your suggestion. True triaxial adsorption and percolation tests are performed separately. The adsorption deformation parameters were obtained by the true triaxial adsorption test, which provided parameter support for the true triaxial seepage test and model.

19. Like the true triaxial adsorption test, the seepage test also showed a turning point, which is similar to the theoretical model of seepage. Can the author also make parameter corrections to keep the two closer?

Response: Thank you for your recognition and valuable comments on this article. In our subsequent research, we will focus on establishing true triaxial adsorption and seepage models. However, this is still in progress.
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