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Research advances in non-Darcy flow in low permeability media

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Abstract: More and more experimental results show that Darcy's law is not fully applicable in low permeability media, and non-Darcy flow has been identified. In this paper we reviewed the research of non-Darcy flow experiments in low-permeability media in recent decades, discuss the existence of non-Darcy flow, and summarize its constitutive equations. The reasons for the threshold gradient were also discussed and summarized for the criterion of the critical point of non-Darcy flow. On this basis, the future development of non-Darcy flow experiments in the rock and clay media were discussed, in order to provide a certain reference for subsequent research on seepage laws in low permeability media.

Keywords: Low permeability media; Non-Darcy flow; Constitutive equation; Critical point criterion

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Introduction

A low permeability medium is a material in which fluid is very difficult to pass through and follows a special penetration law (DENG Ying-er, 2009). The definition of low permeability media varies in different fields. In the field of underground liquid (groundwater, petroleum) resource development in China, the media with a permeability lower than 5×10^{-14} m^2 are seen as low permeability media; in the field of water resources and hydropower engineering, the media with a hydraulic conductivity between 10^{-7} m/s to 10^{-6} m/s are seen as low permeability media. In previous studies, low permeability media were often treated as a relatively impermeable layer (GUO Shang-ping and ZHANG Sheng-zong, 1996; Youn Sim *et al*. 1999; Zimmerman, 2000). However, in recent years, some researchers have discovered that the amount of water flowing through low permeability media cannot be ignored during a long-term hydrogeological process (Neuman and Shlomo, 1972; ZHOU Zhi-fang *et al*. 2004). These water movements, though at a slow rate, will also affect the evolution of geochemical systems, hydrogeological systems, and the formation of petroleum deposits on a long timescale. Its role in the field of seepage research has become more prominent and important.

Darcy's law is the most widely used linear law in seepage mechanics. It was formulated by the French engineer Henry Darcy based on experiments conducted on saturated sands. This law almost accurately interprets the seepage phenomenon and becomes the theoretical basis for subsequent seepage studies. It has been used in many fields, such as groundwater resources evaluation (Akoanung *et al*. 2019), oil and gas reservoir development (XU Jie *et al*. 2011), changes in soil environment (Klípa *et al*. 2014; LIU Wei-

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zong *et al*. 2020) and geotechnical engineering (XIAO Jin-yang, 2019). However, with the development of scientific research, more and more researchers have discovered that when Darcy's law is applied to low permeability media, there will be a non-linear relationship between the seepage velocity and the hydraulic gradient, or there may be deviations such as the threshold pressure gradient (Engelhardt and Tunn, 1955; Hansbo, 1960; Miller and Low, 1963; Mitchell and Younger, 1967; YAN Qing-lai *et al*. 1990). The hydraulic gradient and the pressure gradient are two concepts applied to the groundwater field and the geotechnical and petroleum field respectively. The hydraulic gradient refers to the decrease in hydraulic head per unit distance along the direction of flow in the aquifer. The pressure gradient refers to the pressure change per unit length along the fluid flow direction. Both concepts can be taken as the driving force for the fluid to overcome resistance and flow at a certain rate. The threshold pressure gradient can be viewed as the additional pressure gradient that overcomes resistance to flow, which can be either a hydraulic gradient or a pressure gradient.

It can be seen from the above that if we continue to use the traditional Darcy's law to solve the seepage problem in low permeability media, huge errors may occur in the calculation of seepage velocity, and it will be difficult to accurately evaluate the seepage characteristics of low permeability media. However, few previous researches have provided in-depth and extensive study on non-Darcy flow, most of which are still qualitative analysis, lacking complex and accurate experiments as a basis and a complete non-Darcy flow system to provide guidance for production practice. This paper attempts to discuss the existing research results on the existence, constitutive equation, cause of formation, and critical point criterion of non-Darcy flow in low permeability media, and to explore directions and methods on the development of non-Darcy flow experiments in rocks and clay. This paper is expected to provide reference for solving the seepage problems of low permeability media in the fields such as hydraulic engineering, petroleum engineering, environmental engineering and geotechnical engineering in the future.

1 The existence of non-Darcy flow in low permeability media and its constitutive equation

The permeability and flow law of low permeability media is determined by their own properties. Common low permeability media are clay and rocks which have poorly developed fractures.

1.1 Non-Darcy flow in the clay and its constitutive equation

As early as 1955, scholars Engelhardt and Tunn (1955) obtained sample data of fluids flowing through sandstones with clay contents of 1% to 5%, and discovered the non-Darcy phenomenon. However, the method of measuring the flow velocity was not specified. Then Hansbo (1960), Miller and Low (1963), Mitchell and Younger (1967) measured the flow velocity by observing the displacement and time of the bubble moving in the capillary, from which they obtained data from the pressure-bearing clay samples, and proved the non-Darcy flow phenomenon in low permeability media.

Irmay (Bear, 1983) indicated that there is a minimum gradient J0 through the low-velocity non-Darcy flow experiment of water in the clay. J_0 is the threshold pressure gradient value, meaning that if the actual hydraulic gradient is smaller than J_0, no flow occurs. After introducing the concept of threshold pressure gradient, the equation of motion in clay is obtained:

$$v=\begin{cases}0 & J \le J_0 \\ K\ (J-J_0) & J > J_0\end{cases} \tag{1}$$

In the formula, v is the seepage velocity (cm/s); K is the hydraulic conductivity (cm/s); J is the hydraulic gradient; J_0 is the threshold pressure gradient.

More and more experimental results have proved that at the initial stage, under low pressure gradient, the seepage of low-permeability media is non-linear, and the characteristic curve of low-velocity non-Darcy flow has been obtained (QIN Feng and WANG Yuan, 2009), as shown in Fig. 1. The concave curve segment is the measured non-Darcy flow, and the straight-line segment is the measured Darcy flow.

Swartzendruber (Bear, 1983) analyzed the non-Darcy flow data previously produced in fluid-saturated porous media, and believed that the above phenomenon occurred due to the viscosity of non-Newtonian fluid caused by waterclay interaction. Swartzendruber then concluded the following equation of motion based on experimental data:

$$v=\begin{cases}0 & J\le J_0\\ B\left[J-\exp\left\{-CJ\right\}\right] & J>J_0\end{cases} \quad (2)$$

In the above formula, B and C are constants related to fluid and medium properties; the rest are the same as formula (1).

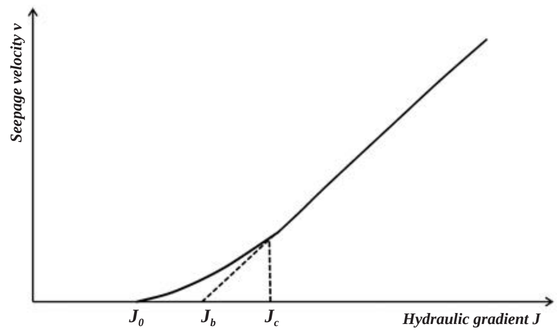


Fig.1 Low-permeability non-Darcy flow characteristic curve

The above two researchers considered threshold pressure gradients and linear segments, while scholar Švec (1979) believed that when fluids flow through low permeability clay media, the pressure gradient and seepage velocity always show a non-linear relationship, and he proposed the equation of motion without linear segment:

$$v = K_n(J - J_0)^2 \quad (3)$$

In this formula, K_n is the hydraulic conductivity (cm/s) of the medium below the lower limit of Darcy's law; the rest are the same as in formula (1) and (2).

Research on the low permeability of cohesive soil media started late in China. QI Tian *et al.* (2007) conducted a consolidation-permeability joint experiment on cohesive soil specimens using a GDS advanced consolidation instrument to investigate the flow in saturated clay under different consolidation pressures. The result showed that the relationship between the seepage velocity and the hydraulic gradient was non-linear, but the threshold hydraulic gradient did not exist. SUN Li-yun *et al.* (2010) did the same experiment using modified consolidometer-permeameter apparatus. They also discovered the deviation from Darcy's law, and concluded that the non-Darcy permeability characteristics was growing with the increase of consolidation pressure. LIU Kai *et al.* (2013) selected four fine-grained soil samples to carry out an indoor one-dimensional soil column seepage experiment. They analyzed the relationship between the hydraulic gradient and the seepage velocity by adjusting the head difference at the inlet and outlet. The experimental results showed that the particle size distribution of the soil sample played a dominant role in the seepage law. Samples with higher the clay content showed more non-Darcy characteristics and had higher threshold pressure gradient. WANG Sheng-wei *et al.* (2018) made soil samples with different proportions of sand and clay to conduct the consolidation-permeability joint experiment. The results showed that when the sand content was less than 50%, the seepage curve started to deviate from Darcy's law, and a threshold gradient appeared. WANG Hai-ke *et al.* (2020) used the TST55 permeameter to conduct constant-head permeability experiments on loess specimens with different dry densities, and the results indicated that there is a threshold hydraulic gradient and a critical hydraulic gradient for seepage in clay.

1.2 Non-Darcy flow in rock media and its constitutive equation

In 1965, in a petroleum permeability experiment Требин (1965) discovered that when the modulus of the fluid pressure gradient is lower than the threshold pressure gradient, no flow occurs, and the equation of motion is obtained as:

$$v=\begin{cases}0 & J<J_0\\ -\dfrac{k}{\mu}J\left(1-\dfrac{J_0}{|J|}\right) & J\ge J_0\end{cases} \quad (4)$$

In the formula, k is the permeability (μm^2); μ is the viscosity (MPa·s); the rest are the same as above.

As early as 1990, YAN Qing-lai *et al.* (1990) conducted single-phase seepage experiments on natural and artificial soil cores with different permeability. They studied the flow curves of distilled water and low saline water flowing through low-permeability cores and simulated oil flowing through oil-permeable cores. The results showed that the seepage curve is nonlinear at low seepage velocity, which becomes quasilinear with higher seepage velocity and a threshold pressure gradient can be identified and indicated by the intercept of the curve section. It was also concluded that the characteristics of the non-Darcy flow curve are directly related to the core's permeability. Subsequently, WU Jing-chun *et al.* (1999) did the same experiment on low permeability oil reservoirs and also confirmed the existence of low-velocity non-linear flow.

HUANG Yan-zhang (1997) proposed three equations to describe the seepage process based on the seepage characteristics featured by a large amount of experimental data. Among them the most accurate one for scientific research and fine engineering is as follows:

$$v=\begin{cases}0 & J<J_0\\ a_1(J)^n & J_0<J<J_c\\ K(J-J_b) & J>J_c\end{cases} \tag{5}$$

In the formula, k is the permeability (10^{-3} μm^2); J_b is the pseudo threshold pressure gradient (Mpa/cm) which is the intercept of the linear section of the seepage curve on the x-axis, in Fig. 1; J_c is the critical pressure gradient (Mpa/cm), which is the abscissa of the turning point from non-linear section to linear section on the seepage curve in Fig. 1. After the critical pressure gradient, the curve becomes a straight line, and the flow follows Darcy's law; a_1 and n are constants related to lithology and fluid properties.

DENG Ying-er (2001) analyzed the characteristics of the transition from the nonlinear section to the linear section on the seepage curve based on the experimental results, and proposed a binomial non-linear seepage model which is a three-parameter continuous function model. This model presents the mechanical law when the interaction between fluid and rock cannot be ignored in the seepage process. The equation is as follows:

$$v[a_1+\frac{a_2}{1+bv}]=J \tag{6}$$

In the formula, a_1, a_2 and b are parameters determined by experiments, and the rest are the same as above.

1.3 The existence of non-Darcy flow in low permeability media is controversial

Although many researchers have noticed the non-Darcy flow in the above two different media experiments, some of them are still skeptical about it. Olsen (1966; 1965) compared the results from capillary tubes exposed to laboratory air for many days and clean ones for permeability experiments. The results showed that the deviation from the validity of Darcy's law caused by atmospheric contamination in the capillary is sufficient to explain the deviations observed in most published experimental data on closed clay samples. He believed that the reasons for the deviation from Darcy's law in previous experiments are the contaminants in the equipment with conventional technique and the long intervals of measurements or high gradients needed for the measurement. ZHANG Ying-ling and ZHU Jing-yi (1991) used air bubbles in a thin tube to measure the flow velocity under constant temperatures, and used consoledometer-permeameter apparatus to test the hydraulic conductivity of nearly 50 undisturbed soil samples at different formation depths in Hebei, Shanxi and Wuhan under no pressure, natural pressure and pressurized conditions. The results showed that the permeability of these saturated viscous undisturbed soil samples is in compliance with Darcy's law. WANG Xiu-yan *et al*. (2003) used a modified triaxial tester and permeameter-consolidometer apparatus to carry out rigorous permeability experiments on 50 groups of original samples. Although the results showed that the seepage curve in the clay was nonlinear, no threshold hydraulic gradients nor critical hydraulic gradients could be clearly identified. WANG Hui-ming and LIU Chang-li (2003) summarized the reasons for denying the existence of non-Darcy flow: ① the high pressure gradient applied for flow measurement distorted the experiment results; ② the researchers followed traditional thinking to regard anomalies as errors and ignored the non-Darcy phenomenon.

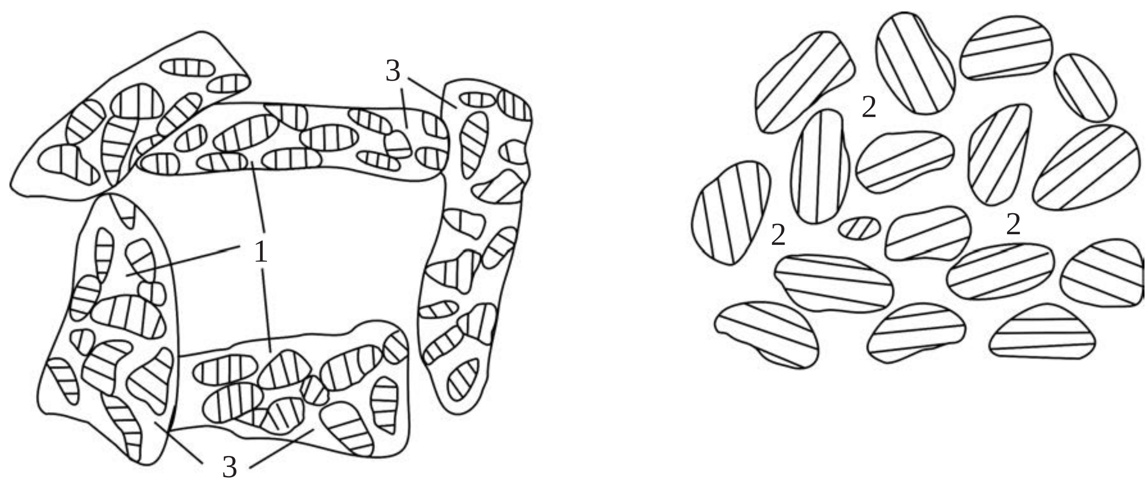
After discussing the existence of non-Darcy flow in low permeability media and its constitutive equation, we realized that after many domestic and foreign researchers have conducted relative studies for more than half a century, the existence of non-linear seepage in low permeability media is still controversial. However, most researchers believe that Darcy's law only applies under certain conditions, and the natural seepage is generally nonlinear. Also, different researchers have developed formulas with different emphases based on specific experiments and theoretical analysis. However, due to the diversity of experimental fluid and low permeability medium, most of the parameters in their equations are to be determined and subject to human factors. Therefore no universal equation of motion has been developed and there is still a lack of a well-recognized mathematical model for low-velocity non-Darcy flow.

2 Cause analysis of non-Darcy flow in low permeability media

Since the discovery of the non-Darcy flow, many researchers have explored its causes, and the major findings are as follows:

2.1 Pore structure of low permeability media

Chinese scholar FENG Xiao-la (1988) analyzed the pore structures in the soil with a large number of scanning electron microscopy photos, and divided water in the soil into three forms based on its type of location in the soil: (1) water in the contact part of the aggregates; (2) water in the pores of the aggregates and (3) water in the pores between the aggregates. Then the author used the differences of the three forms of water flow to explain the non-Darcy flow characteristics in clay with different compaction densities. Some scientists believed that there are both macropores and micropores in the clay, and the seepage law in saturated clay is essentially the mutual transformation of gravitational water and bound water in these two kinds of pores (SU Qing-shan and DUAN Shu-juan, 1994; XU Chuan-fu, 2008). In macropores, water exists mainly in the form of gravitational water, meaning that as long as there is a hydraulic gradient, seepage occurs, and its seepage follows Darcy's law. In micropores, water exists mainly in the form of bound water which can only flow under a certain hydraulic gradient, and the flow does not conform to Darcy's law. CHEN Jian *et al*. (2019) believed that the deviation from Darcy's law in the clay is caused by the pore distribution and the electric double layer effect on the surface of clay. He considered these two factors and proposed the seepage theory with the pore size effect based on the microscale seepage of the circular tube model. Through the mercury intrusion test, the internal pore distribution of the soil sample is obtained, and cumulative distribution function of porosity is used to explain the percentage of pore size in the clay and the contribution of pores with different size to the seepage in the clay, which significantly improves the calculation accuracy of the hydraulic conductivity in the clay.



1. Isolated pores; 2. Inter-aggregate pores; 3. Intra-aggregate pores

Fig. 2 Pores in the clay (FENG Xiao-la, 1988)

In rock media, consolidated rocks such as shale, mudstone, and carbonate rocks have narrow pore throats, poor connectivity and homogeneity, which lead to their low permeability. Fluids need to overcome great resistance when passing through such media and then non-Darcy flow occurs. Prada and Civan (1999), YAN Qing-lai (1990), YAO Yue-dong and GE Jia-li (2000), WU Jing-chun (1999) and others have used low saline water to conduct single-phase seepage experiments on natural and artificial rock cores with different permeability. Non-linear flow curves are obtained, and the non-linear flow characteristics of different rock samples are different. The same fluid flowing through different rock masses presents different non-linear seepage characteristics, which fully demonstrates the influence of pore structure characteristics on seepage in the rock media.

2.2 Non-Newtonian properties of seepage fluids

The properties of the fluid mainly include viscosity and density. Non-Newtonian fluids are ubiquitous in nature and crude oil is one of them. Due to its high viscosity or extremely low fluidity, when it passes a low permeability medium, the seepage velocity drops sharply. A study (HUANG Yan-zhang, 1998) found that with the increase of fluid viscosity, the the non-linear section of the seepage flow curve becomes longer, the curvature of the curve becomes smaller, the critical pressure gradient and the threshold pressure gradient becomes higher, and the non-linear characteristics is more obvious. When the viscosity decreases to a certain value, the seepage flow changes from non-linear flow to Darcy flow, both the critical pressure gradient and threshold pressure gradient approach zero. Therefore, the viscosity and density of the fluid combinedly determine the occurrence of non-linear flow (LI Zhong-feng *et al*. 2005).

2.3 Interaction between media and fluids

(1) Surface interactions between phases.

LIU Xiao-xu *et al*. (2006) studied the microscopic mechanism of gas seepage in water-bearing gas reservoirs by means of continuous photographs of thin slice seepage. It was observed that the water film on the pore surface accumulated and blocked in the throat under the action of the pressure difference, and the gas started to flow only after the energy reached a certain amount. Therefore, the migration of the water film on the pore surface and their deformation and blockage in the throat were the essential reasons for the low-velocity non-Darcy flow of gas. In the clay media, the thin wafers that make up the clay attract the polar molecules of water. When the fluid flows through the clay, a firm hydration shell will be formed on the pore walls, which will also block the pores (WU Jing-chun *et al*. 1999). In the rock media, absorption may occur between the active material on the fluid surface and the surface of the rock particles, from which an adsorption layer forms and makes the pore throats narrower or even blocked, as a result, the permeability and the seepage velocity decreases. Dense rocks may seep the salt components in the water, so that the salts will be filtered and precipitated, and then block the pore throat.

(2) The specific surface area of the reservoir

HUANG Yan-zhang (1998) believes that the specific surface area is inversely proportional to the square root of permeability. A larger specific surface area of the rock indicates a stronger molecular force between the fluid and the solid surface, which will affect the distribution and seepage characteristics of the fluid in the pore system. For example, clay minerals, which have a large specific surface area and free energy, can interact preferentially with foreign fluids that intrude the formation, increase the volume of the water-absorbing clay, and cause a sharp increase in seepage resistance.

(3) Physical and chemical processes in seepage.

The intrusion of foreign fluid into the oil layer normally produces adverse effects, which could be that the physical processes and chemical reactions between the foreign fluid and the reservoir fluid, or between the fluid and the rock cause a decrease in porosity and permeability (JIA Zhen-qi and ZHANG Lian-zhong, 2001).

(4) Coupling of multiple factors

Dense media such as clay and rocks have the ultrafiltration characteristics of membranes, so the flow in these media appears as coupled seepage (Neuzil, 1986). Darcy's law is only a special case describing the law of seepage under the action of hydraulic gradient. In addition, the chemical gradient, potential gradient, and temperature gradient can also cause seepage (WANG Hui-ming *et al*. 2003).

3 Criteria for the critical point of non-Darcy flow in low permeability media

So far, there has not been an accurate and recognized criterion for the transition from non-Darcy to Darcy flow while many researchers have been actively working on it. The Reynolds number, which represents the comprehensive influence of reservoirs, physical properties of fluid (reservoir porosity, permeability, fluid density, viscosity) and development conditions (seepage velocity or pressure gradient), has been preferably considered as a criterion for non-Darcy flow thresholds.

Chilton and Colburn (2002) were the earliest ones who proposed to use the Reynolds number

(Re) to describe the state of water flow in porous media, and analogized it to pipe flow. Re was defined as:

$$R_e = \frac{v\rho d}{\mu} \tag{7}$$

In the formula, v is the seepage velocity (m/d); ρ is the fluid density (kg/m^3); d is the particle size of the medium particles (μm); μ is the viscosity coefficient (Pa·s).

Considering that the accurate diameter of the media particles is difficult to determine, Green *et al*. (1951) redefined the Reynolds number by using the hydraulic conductivity K of the porous media and the non-Darcy parameter β:

$$R_e = K\beta \frac{vp}{\mu} \tag{8}$$

In the formula, all parameters and their units are the same as above. LIU Jian-jun *et al*. (2003) conducted physical experiments of seepage on nearly one hundred low-permeability cores, and found that the critical Reynolds number for the transition from linear to non-linear seepage is about 10^{-6}. LI Zhong-feng *et al*. (2005) did similar experiments on a large number of low-permeability cores. The results showed that as the Reynolds number decreased, the conditions of Darcy's law became invalid, and the seepage gradually transitioned to non-linear. They also concluded that the critical Reynolds number was about 8.95×10^{-5}, and the critical Reynolds number for transition from ultra-low velocity zone to low velocity zone was about 1.08×10^{-6}. WANG Dao-cheng *et al*. (2006) applied the low-velocity non-Darcy flow method on low-permeability reservoirs, and found that the critical Reynolds number of the non-Darcy flow for oil-oil displacement under the condition of bound water saturation was 5×10^{-4}, and the critical Reynolds number of non-Darcy flow for water-water displacement under the condition of residual oil saturation was 1×10^{-3}. It can be seen from the above that the critical Reynolds number is not a fixed value, and it varies with type of media, experimental methods and techniques. Therefore, it is not convincing to use Reynolds number alone to determine whether the seepage follows Darcy's law. RUAN Min *et al*. (1999) suggested that factors such as fluid viscosity μ and density ρ, rock's permeability k and pore radius r have great influence on the pseudo-threshold pressure gradient. After comprehensive consideration of the above factors, the concept of pressure number λ_N is introduced in the comprehensive discriminant of low-permeability non-Darcy flow through dimensional analysis method:

$$\lambda_N = \frac{\mu^2 \mathrm{R}}{k\rho r} \tag{9}$$

In the formula, $\frac{R}{r}$ is the pore-to-throat ratio, and the rest are the same as above. Through experimental analysis, it is concluded that when λ_N >5, the flow exhibits non-Darcy flow characteristics; when λ_N <2, the flow appears as Darcy's linear flow; when 2< λ_N <5, this is a transition zone between the two. However, this theory fails to consider the impact of dynamic factors. For example, with the change of the dynamic conditions, under a higher pressure gradient, the fluid that was motionless also starts to flow, which inevitably changes the original seepage pattern.

The above conclusions are drawn under a certain seepage environment, therefore the determination method is not universal. Currently, research on criteria for the critical point of non-Darcy flow in low-permeability media mainly focuses on the field of oil and gas reservoirs and seepage in rock, while few studies have been conducted on the clay media. In the future research, it is suggested to apply the Reynolds number method and the pressure number method on clay to demonstrate their applicability.

4 Conclusions

This paper analyzes and summarizes the research in the field of non-Darcy flow in low permeability media in recent decades, and makes the following conclusions:

(1) Although many researchers have noticed non-Darcy flow in experiments with low permeability media, some of them still question the existence of it. Based on different experimental data, researchers have derived constitutive equations with different focuses. According to the characteristic of non-Darcy flow, these equations can be roughly divided into three categories: A linear model that ignores the non-linear section, a polynomial model that ignores the linear section, and a model that considers both the linear and non-linear sections

(2) The factors that cause the non-Darcy flow

of low permeability media mainly include the pore structure of the medium, the non-Newtonian nature of the seepage fluid, and the interaction between the medium and the fluid.

(3) Currently, the research on criteria for the critical point of non-Darcy flow in low permeability media mainly focuses on the field of oil and gas reservoirs and seepage in rock , while few studies have been conducted on the clay media. In addition, all conclusions have been drawn under a certain seepage environment, which are not universal.

5 Outlooks

Seepage in low permeability media is a challenging research topic. Currently, the research on seepage in rock media is developing rapidly and comprehensively, but it is still controversial whether it deviates from Darcy's law in the clay. Since clay is an excellent natural waterproofing material, it is of great significance to determine the seepage law of water in the clay for the protection of water and soil environment. Therefore, more attention should be put on seepage in the clay in the following research. The future study of non-Darcy flow in low-permeability media can be carried out in the following three aspects:

(1) The influence of experimental conditions and scale on the results

In the previous research, whether the nonlinear deviation in the seepage experiment is caused by the experimental conditions has not yet been determined. Therefore, in the future seepage experiments, the experimental equipment, conditions and process are expected to be improved and more standardized. Samples should be increased and well classified, so that more accurate conclusions and more practical constitutive equations can be obtained. In addition, the existing seepage experiments are mostly small-scale indoor studies. Problems such as height limit of samples, single seepage direction, and the application of high pressure gradients applied to speed up the flow measurement but cause distortion. In the future, researchers can carry out multi-scale seepage experiments, increase the experimental scale, and try to apply the laboratory conclusions to the field by restoring the practical conditions, thus to enhance the reliability and feasibility of the experimental results.

(2) Change in structure of the medium and fluid seepage law under different pressures

With the rapid development of electronic technology, scanning electron microscopes, transmission electron microscopes and other equipment have been used to observe the microscopic configuration of rock and soil, which helps to explain the occurrence of non-Darcy flow in low permeability media. In the future studies, the internal microstructure of the low permeability media can be quantitatively analyzed, and the pore throat radius of the soil can be used as the criterion for the critical point of non-Darcy seepage in the clay. It is very important to observe the structural changes of clay and the seepage of water molecules under different water pressures. The mechanism analysis of seepage in different types of clay will shed new light on the study of microstructure and permeability of clay. In the rock media, high-tech technology can be used to visualize the interior of the rock, and explore the effects of internal development problems such as pore structure and capillary action on the seepage process.

(3) The influence of other factors on the seepage process

In addition to the structure of the medium itself and hydraulic gradients, the chemical, temperature and potential gradients in the medium also have effects on seepage, so it is a complex multi-field coupling problem in the real environment. There are many uncertain factors when extrapolating experimental results to real problems. Therefore, the multi-field seepage coupling theory should be used in the future experiments and quantitative analysis of seepage in low permeability media.

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