Proceedings World Geothermal Congress 2023
Beijing, China, April 17 – 21, 2023

Clogging caused by coupled grain migration and compaction effect during groundwater recharge for unconsolidated sandstone reservoir in ground water-source heat pump

Fujian Yang[1, 2], Jing Luo[3], Hejuan Liu[1, 2], Dawei Hu[1, 2*], Hui Zhou[1, 2]

1 State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China.

2 University of Chinese Academy of Sciences, Beijing 100049 China.

3 Sinopec Star Hubei New Energy Development Co., Ltd., Wuhan 430010, China.

Corresponding author: Dawei Hu (dwhu@whrsm.ac.cn)

Keywords: Ground Water-Source Heat Pump; Clogging; Grain Migration; Groundwater recharge; Unconsolidated Sandstone

ABSTRACT

A large number of movable grains and complex grain size composition exist in unconsolidated sandstone reservoir (USR), thus, knowledge of the clogging caused by the coupled effect of grain migration and compaction of in-situ stress and the effect of grain size on grain migration are significant for groundwater recharge of the ground water-source heat pump. For this, a series of seepage experiments were conducted under in-situ stress for the unconsolidated sandstone samples with different grain compositions. Coupled effect of grain migration and compaction of in-situ stress is one of the important reasons for the recharge clogging for USR. Firstly, the original fine grains are migrated along seepage direction, and the pores are created by grain migration. Then, the skeleton structure constructed of coarse grains is reconstructed under the compaction effect of in-situ stress, and the stress field of coarse grains is redistributed, resulting in the coarse grains are crushed into fine grains. Furthermore, the migration of original and secondary crushed fine-grain blocks the seepage channel. An obvious threshold of grain size, 0.5 mm, is exhibited for grain migration and transportation property, where the apparent permeability experiences a transition from stability to decrease for samples composed of smaller grain (< 0.5mm), whilst the apparent permeability skips a stability stage and goes directly into the decrease stage, and even that exhibit a slight increase for samples with a larger grain (> 0.5mm). A unique failure mode, diameter shrinkage in the upper part of the sample, is presented due to the coupled effect of grain migration and the compaction effect of in-situ stress. Some measures taken in the field are exhibited, and their advantages and disadvantages are given. Furthermore, the applicability of the common methods in solving recharge clogging caused by grain migration is discussed. Fortunately, methods that regular alternate injection and extraction of flows in the well could be a potentially effective measure. The testing results in this context could facilitate our understanding of the clogging caused by coupled grain migration and compaction effect during groundwater recharge for USR in ground water-source heat pump, and the potentially effective measure could be provided in the field.

1. INTRODUCTION

Ground water-source heat pumps (GWHPs) are identified as an effective method for reducing energy demand and consumption (Athresh et al., 2016). It has been widely used in countries such as the US, the UK, China, Sweden, and Japan (Lund, 2009). However, GWHPs are still facing challenges in technology application (Ståhl et al., 2000; Nian et al., 2018b, 2019). Especially, clogging is often an inescapable issue during groundwater recharge (Chen et al., 2017; Chu et al., 2019; Li et al., 2020a, 2020b, 2021; Liu et al., 2021). Statistics show that 80% of recharge wells have different degrees of clogging in the field, even some wells have to abandon (Caulk et al., 2017). Clogging can be divided into three categories based on the controlling factors such as physical clogging, chemical clogging, and biological clogging (Chapelle, 1992; Baveye et al., 1998; Katarzyna, 2006; Xu et al., 2011; Xia et al., 2014, 2016; Bustos Medina et al., 2013; Cui et al., 2018; Wang et al., 2018b; Ng et al., 2020; Ping et al., 2020; Zhang et al., 2020b). Physical clogging by suspended grains and grain migration is the most common clogging mechanism, which accounts for 55 % of all clogging (Bouwer et al., 2002). Grain migration is often unavoidable due to the self-generated movable grain in reservoirs, especially for unconsolidated sandstone reservoirs (Zhang et al., 2020b). For example, in the Jianghan plain of South China (Wang et al. 2020a), a large number of movable grains exist in sandstone reservoirs with poor cementation, which may lead to serious clogging issues during groundwater recharge.

Various investigations have been carried out about the clogging caused by suspended grains in recharge water for the porous reservoir. Iwasaki et al. (1937) gave a pioneer work, who investigated the degrees of penetration of suspended grains considering the size of suspended grains and the filtering velocity and proposed a theoretical model of grain capture and permeability reduction in the sand filter bed. The investigation of Morten et al. (1986) and Selby et al. (1988) shown that the clogging caused by suspended grains in porous media was affected by various factors, including the flow rate of the liquid, sand size, and the initial content, shape, size of the fine particles. Besides, Rosenbrand et al. (2012, 2014, 2015) and Kanimozhi et al. (2021) presented laboratory modeling of fines migration in the porous sedimentary aquifer under geothermal conditions and found that the detachment of clay mineral fine grains was closely related to temperature, and the migration of fine particles were the main reasons causing the decrease of reservoir permeability. A series of flooding experiment was performed by Yu et al. (2018) and Redekop et al. (2021) on sandstone samples, analysis of fines migration during water flow with salinity alteration, where the clay mineral fine grains was detached and induced permeability damage during freshwater waterflooding, about 80% decrease in permeability. However, the results of Badalyan et al. (2014) indicated the damage caused by the detachment of clay grains in the reservoir due to low salinity of recharge water was greater than the damage caused by suspended grain migration in rejection water. Furthermore, the migration mechanism of clay grains and prevention measures in porous media was studied by Russell et al. (2018) and indicated that adding CaCl2 in high-salinity recharge water could increase calcite content in a reservoir and reduce clay particles detaching from the mineral surface.

Previous studies mainly focused on the clogging caused by the migration of suspended grain in the recharge water and its influencing factors (e.g. grain size, initial content, and flow rate, etc.), and the detachment of clay mineral in a reservoir and its influencing factors (e.g. temperature and salinity). These results are mostly applicable to rocks reservoir with good cementation. Besides, the suspended grain clogging is caused by filling the original reservoir pores, which enhances the resistance to deformation of the reservoir to a certain extent (Chu et al., 2019). However, for the sandstone reservoir with a high mud content and poor cementation, there are a large number of movable grains and a complicated grain size composition, where the movable grains are detached from the host reservoir and then migrated during groundwater recharge. Thus, the pores are created by the grain migration for the host reservoir. Under the compaction of in-situ stress, the host reservoir will also be deformed, which in turn affects grain migration. However, the coupled effect of grain migration and the compaction of in-situ stress on clogging in unconsolidated sandstone reservoirs (USR) are rarely reported. However, it should be pointed out that the grain migration mentioned in this paper refers to the migration of movable grains of USR itself, rather than the migration of suspended grains in the recharge water.

For this, the coupled effect of grain migration and compaction effect of in-situ stress on clogging is investigated during groundwater recharge for USR. Considering the complication of grain size composition of USR, the effect of grain composition on grain migration is also considered in this paper. Thus, a series of seepage experiments were conducted by increasing flow rate under in-situ stress for the samples with different grain compositions. The clogging mechanism caused by the coupled effect of grain migration and the compaction effect is clarified, and the effect of grain composition on grain migration is exhibited.

2. MATERIALS AND METHODS

2.1 Background of a geothermal field in the USRs

Jianghan oilfield, where the abundant geothermal resources can be utilized, especially for hydrothermal geothermal energy, is located in Jianghan Plain, Hubei Province, China (please see Figure 1). Statistics show that there are more than 2,500 abandoned oilfield wells in Jianghan oilfield till 2016, which presents an interesting opportunity to be retrofitted as a geothermal system as they are generally deep enough to access high temperature (Cheng et al., 2014). The aquifers extracted are mainly Neogene Guanghuasi formation, with burial depths of 600~700 m and poor cementation, is composed of unconsolidated sandstone, which is overlaid by Quaternary sedimentary formations. The porosity ranges from 24.9% to 43.8% and the mean porosity is 36.5%. The pressure coefficient (i.e., the ratio of initial pore pressure to the hydrostatic stress of the stratum) is about 1.0, implying that the USR is a normal pressure system. The properties of USR are shown in Table 1.

Up to now, the Jianghan oilfield owns the largest GWHP system in Central China, including 22 pumping wells and 20 recharge wells, with an injection-production ratio of 0.91. The well depth is in a range from 613.07 m to 784.47m, and the diameter of the well is 177.8 mm. The water yield of a single well is above 120 m3/h. The filtration system consisted of a coarse filter and fine filter for the GWHP system, and the purification treatment of the recharge water meets the requirements of industry standards, with filter accuracy less than 5um, according to the Standard for Technical Requirement for geothermal reinjection (NB/T 10099-2018). However, the sand production was clearly observed in the extracted geothermal water (Figure 2), and the grain content and size are much larger than that in the recharge water. This indicates a lot of movable grains are detached and then migrated in USR located in Jianghan oilfield. Meanwhile, the obvious clogging was presented in recharge wells. For example, the recharge pressure of the 2# recharge well was increased from 0.25 MPa to 0.80 MPa, and the recharge rate was dropped to 43% from 85%. For this, the variation of apparent permeability of unconsolidated sandstone during groundwater recharge considering the time effect has been presented by our previous study (Yang et al., 2019). On this basis, an extended investigation is carried out in this paper to understand the coupled effect of grain migration and the compaction effect of in-situ stress on recharge clogging for USR, and the effect of grain composition on the grain migration. To avoid the mutual influence of multiple factors for recharge clogging, the suspended grains in recharge water, biological factors, and chemical factors are not considered in this paper. Meanwhile, some measures were adopted such as the sterilized distilled water was used as recharge water in seepage experiment.

Table 1 Physical properties of the geothermal reservoir

In-situ stress (MPa)	Formation pressure coefficient	Grains density (g/cm^3)	Saturated density (g/cm^3)	Porosity %
12.50	1.0	2.7	2.2	36.5

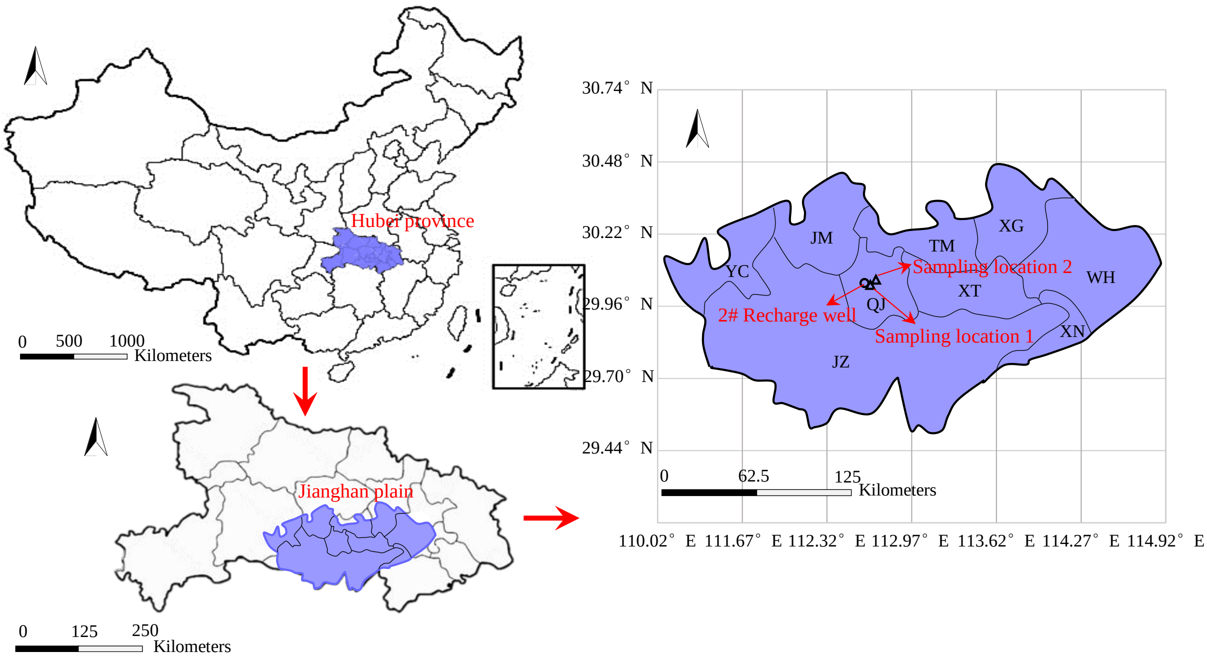


Figure 1: Figure 1 Location of the field site of Jianghan oilfield in Qiangjiang (QJ) city, Hubei province, China, and the location of 2# recharge well, and the sampling locations 1 and 2 of unconsolidated sandstone. The Jianghan plain includes cities such as Yichang (YC), Jinmen (JM), Tianmen (TM), Xiaogan (XG), Wuhan (WH), Xianning (XN), Jinzhou (JZ), Qianjiang (QJ), and Xiantao (XT).

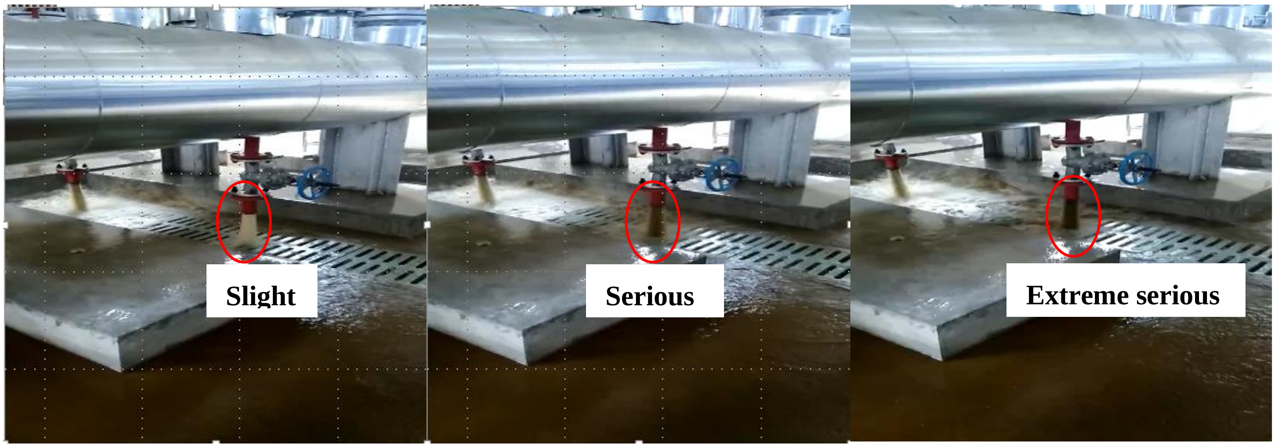


Figure 2 Sand production in the extracted geothermal water

2.2 Experimental material

The unconsolidated sandstone was obtained from the same rock formation and different locations (Location 1 and Location 2) using the core drilling machine, where Location 1 is located near 2# recharge well with a depth of 651.40 m, and the grain size distribution curves are shown in Figure 3. The location of the recharge well and the sampling locations are given in Figure 1. The depth of sampling Locations 1 and 2 are 655.00 m and 647.20 m, respectively, and the distance between the two is 200 m. The unconsolidated sandstone obtained from near 2# recharge well (Location 1) was selected as experimental material, which is mainly composed of several minerals including quartz (59.25%), feldspar (14.48%), and clay minerals such as montmorillonite (11.65%), illite (9.86%), and kaolinite (4.76%), etc. The unconsolidated sandstone extracted is characterized as argillaceous cementation and poor cementation, The cylindrical samples with a diameter of 50 mm and a length of 100 mm were prepared for the seepage experiments based on the reservoir conditions including the saturated water content, density, and porosity.

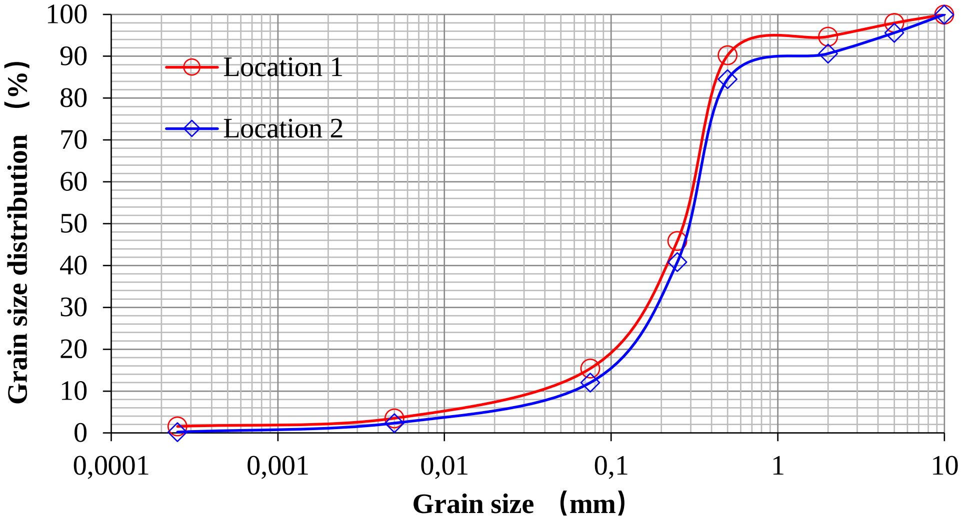


Figure 3 Grain size distribution curve of collected unconsolidated sandstone sample in different locations

2.3 Testing scheme

This work mainly focuses on the coupled effect of grain migration and compaction effect of in-situ stress on recharge clogging for USR, and the effect of grain composition on grain migration for the USR. The parameters such as saturated water content, density, porosity, and in-situ stress that were reached in the field, and reproduction all these conditions in laboratory experiments. The seepage experiment work was divided into four steps. Firstly, the unconsolidated sandstone obtained from the field was dried to a constant weight, then the dried unconsolidated sandstone was divided into six groups based on grain size, followed by the preparation of sample according to the parameters (i.e. saturated water content, density, and porosity) obtained in the field, and finally, the seepage experiments were performed by increasing flow rate under in-situ stress for the samples with different grain composition.

2.4 Sample preparation

The unconsolidated sandstone obtained from the Jianghan oilfield was dried to a constant weight under the constant temperature of 105 ℃ using XL101-3 drying oven (the accuracy is ±1℃). Then, the dried unconsolidated sandstone was divided into six groups as shown in Table 2, using the standard test sieve (National Standard (China): GB/T6003.1-2012) with the mesh size equal to 0.075 mm, 0.25 mm, 0.5 mm, 1.0 mm, 2.0 mm and 5.0 mm respectively.

The cylindrical samples consisting of dual grain size and natural gradation were prepared for the seepage experiment according to the parameters such as saturated water content, density, porosity obtained in the field. Firstly, the weight of dry sand and water required for a sample that has similar properties (e.g. density, porosity, and saturated water content) with the USR was calculated by equations (1)-(5). Then, the dry sand and the sterilized distilled water were evenly mixed in a glass container and were placed in a mold with a diameter of 50 mm and a length of 150 mm. Finally, the mold was placed on a compression testing machine, where the machine was loaded in displacement mode until the prepared sample height is equal to 100 mm. The force was kept stable until the sample height does not rebound so that a standard sample with a diameter of 50 mm and a length of 100 mm was prepared. The sample preparation process is shown in Figure 4, the preparation curve is shown in Figure 5, and the physical parameters of prepared samples are shown in Table 3. Besides, the prepared samples were wrapped using a thermal shrinkable tube and saturated with the sterilized distilled water using the H15558 vacuum pump for 24 hours (the accuracy is ± 0.25%).

$$n = \left(\rho_s - \rho_{rs}\right) / \rho_s \times 100\% \tag{1}$$

where n is the effective porosity of the unconsolidated sandstone reservoirs, 36.5 %; ρ_s is the grain density of unconsolidated sandstone, 2.7 g/cm^3; ρ_{rs} is the dry density of the prepared sample of unconsolidated sandstone, g/cm^3.

$$\rho_{rs} = \rho / \left(1 + \omega\right) \tag{2}$$

where ρ is the wet density of the unconsolidated sandstone reservoirs, 2.2 g/cm^3; ω is the saturated water content of the prepared unconsolidated sandstone sample, %.

$$\omega = m_{wat} / m_s \tag{3}$$

where m_{wat} is the water mass of the prepared sample, g; m_s is the mass of solid grains of the prepared sample, g.

$$m = m_{wat} + m_s \tag{4}$$

where m is the mass of the prepared unconsolidated sandstone sample, g.

$$\rho = m / V \tag{5}$$

where V is the volume of the prepared unconsolidated sandstone sample 196.35 cm^3.

Table 2 Classification of grain size

Groups	I	II	III	IV	V	VI
Grain size (mm)	<0.075	0.075 ~ 0.25	0.25 ~ 0.5	0.5 ~ 1.0	1.0 ~ 2.0	2.0 ~ 5.0

Table 3 Physical parameters of the prepared unconsolidated sandstone samples

Sample category	Name (Garticle grade)	Diameter (mm)	Height (mm)	Density ($g\cdot cm^{-3}$)	Saturated water content (%)	Porosity (%)
Dual grain size	A (I+II)	49.58	100.18	2.23	28.32	36.49
	B (II+III)	49.68	100.08	2.23	28.32	36.54
	C (III+IV)	49.87	100.15	2.21	28.32	36.50
	D (IV+V)	49.91	100.07	2.21	28.32	36.51
	E (V+VI)	49.25	100.15	2.26	28.32	36.52
Natural gradation	F (I~VI)	49.71	100.09	2.22	28.32	36.49

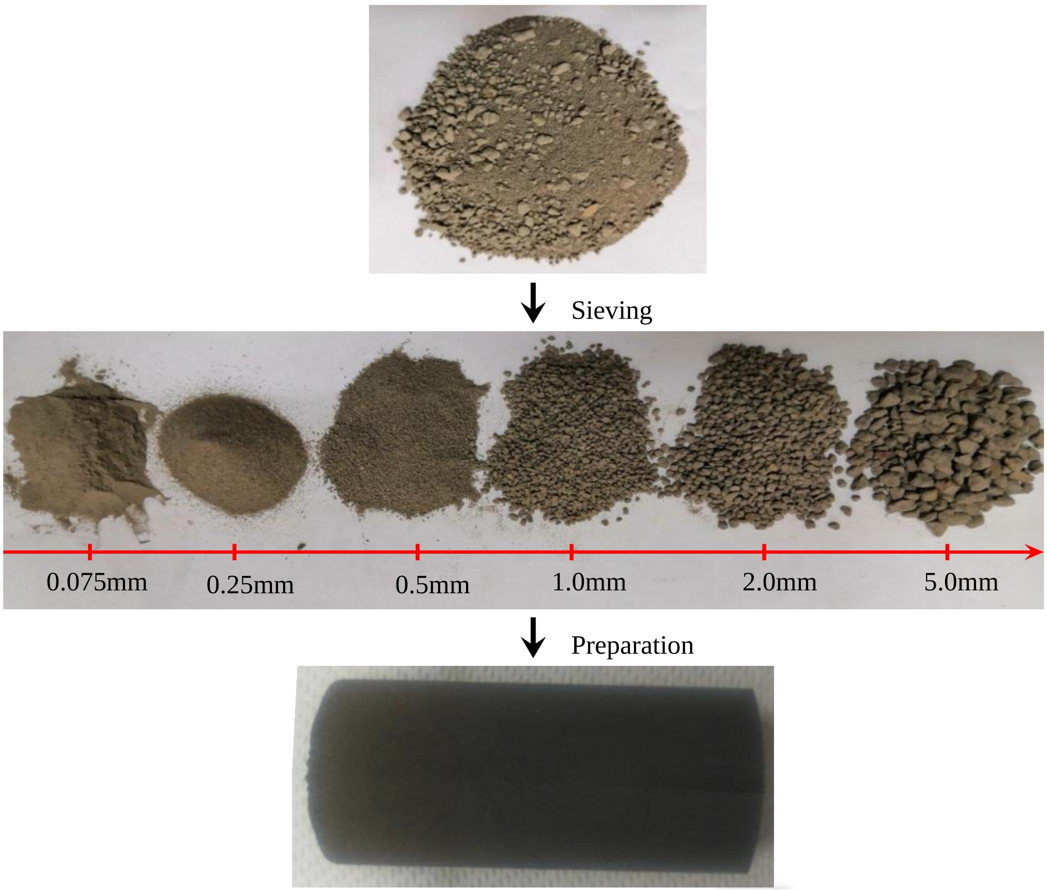


Figure 4 Process of sample preparation

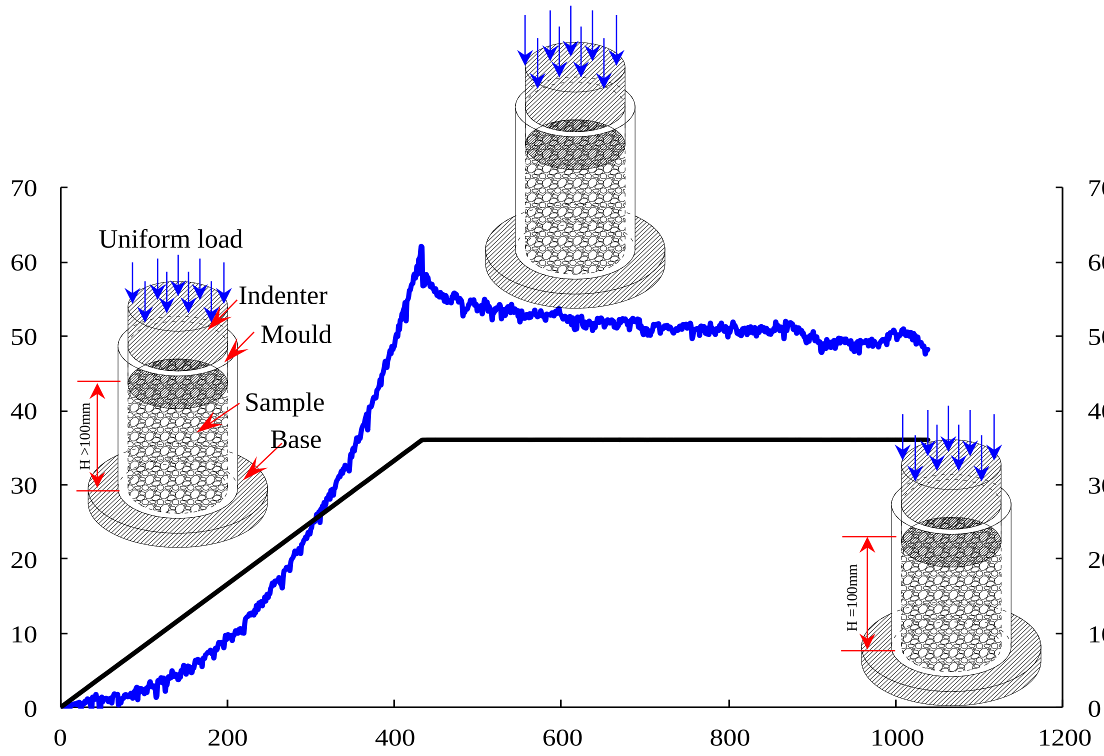


Figure 5 Sample preparation process and preparation curve

2.5 Methods for seepage experiment

The seepage experiment was performed using the high hydrostatic stress core seepage setup, which was developed in Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. The system consists of four major components: core holder system, hydrostatic stress loading system, pore pressure loading system, and data acquisition system. The maximum pore pressure of 45.00 MPa can be applied with the accuracy of 0.01 MPa, and the maximum hydrostatic stress of 60.00 MPa with the accuracy of 0.01 MPa can be loaded. Both can be applied in two modes, i.e., the constant stress loading and the constant flow loading. The schematic of the test system is shown in Figure 6.

Saturated unconsolidated sandstone samples were placed in the high hydrostatic stress core seepage setup. Two seepage plates with a full circular diversion trench (Figure 7) were placed at the ends of the prepared sample, where the sterilized distilled water flowed along the radial guide grooves and moved in the axial direction through the holes in guide grooves. Hydrostatic stress was loaded to 12.50 MPa and was kept at a constant. After the deformation of the sample was stable, the seepage experiment was performed, and the apparent permeability of samples was calculated under different flow rate conditions. At the beginning of the test, the applied flow rate was 0.10 ml/min. The pore pressure was recorded when the outlet of the high hydrostatic stress core seepage setup evenly drops and the pore pressure was stable. Then, the flow rate was increased step by step until the failure of the prepared sample. The schematic diagram of permeability measurement is shown in Figure 7, which is an enlarged view of Part I in Figure 6. The applied mode of the flow rate is as follows:

$$0.1\ \text{ml/min} \xrightarrow{+0.1} 1.0\ \text{ml/min} \xrightarrow{+0.25} 6.0\ \text{ml/min} \xrightarrow{+0.5} \text{Failure of a prepared sample}$$

Darcy's law (i.e. Eq. 6), is adopted to calculate the apparent permeability, where the flow rate can be calculated by equation (7).

$$K_{ap} = \frac{\mu}{J_{rt}} v \tag{6}$$

where K_{ap} is the apparent permeability of the prepared sample, which varies with grain migration or pore structure reconstruction, m^2; μ is the dynamic viscosity coefficient, 1.005×10^{-3} Pa•s; J_{rt} is the pore pressure gradient in real-time, MPa/m.

$$v = \frac{14.4Q}{A\varphi} \tag{7}$$

where v is the flow rate, m/d; Q is the flow, ml/min; A is the cross-sectional area of the prepared samples, cm^2; φ is the porosity of the prepared samples, %.

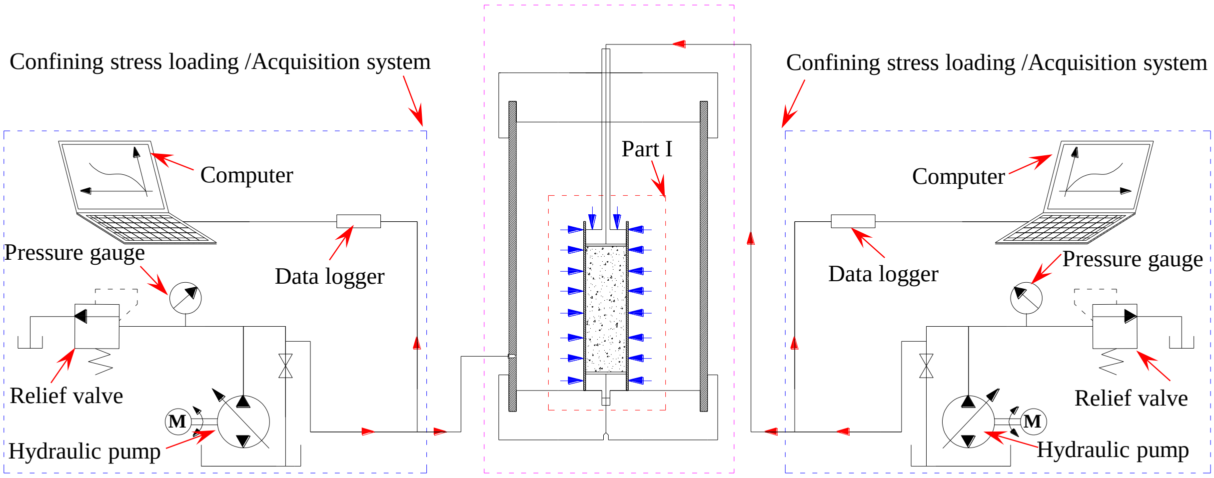


Figure 6 Schematic diagram of the seepage test system

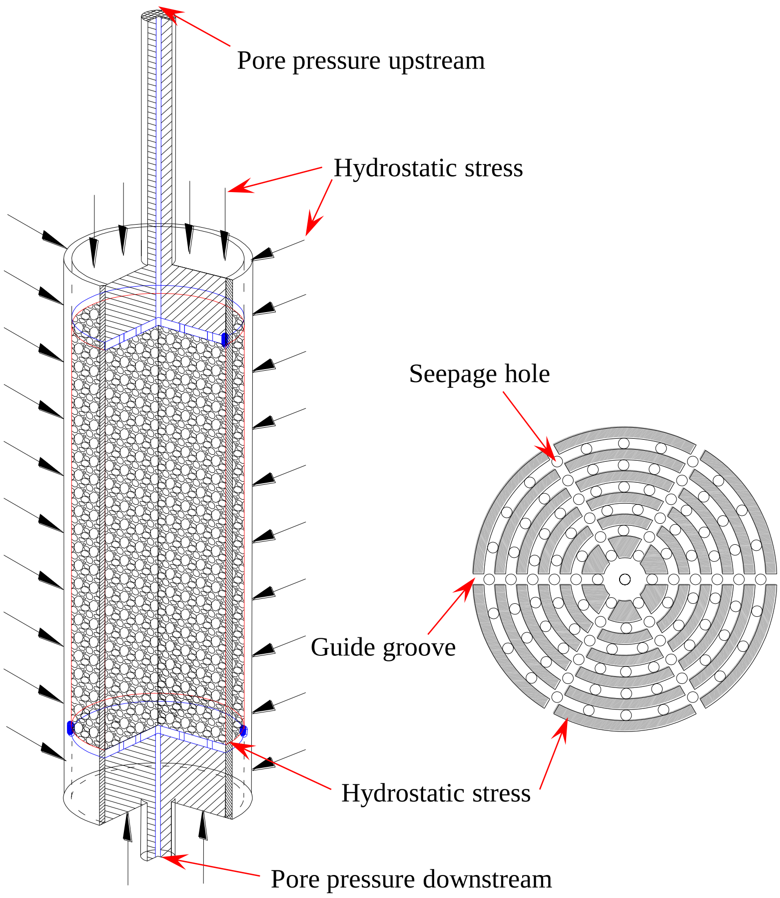
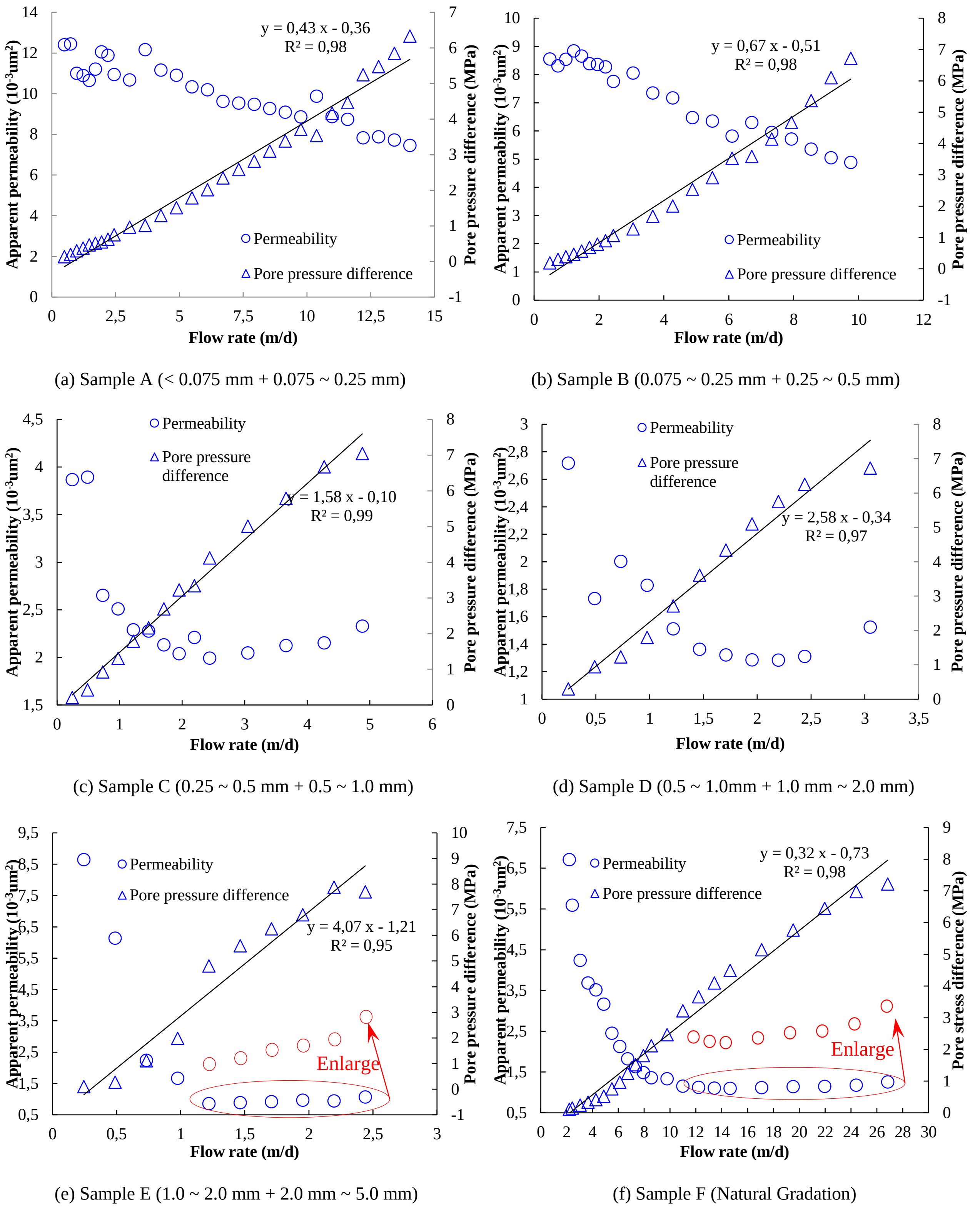


Figure 7 Schematic diagram of permeability measurement (Enlarged view of Part I in Figure 6)

3. RESULTS

The permeability characteristics of unconsolidated sandstone with different grain compositions under in-situ stress equal to 12.5 MPa are exhibited in Figure 8. The results show that there is a significant linear relationship between the flow rate and the pore pressure difference, which is consistent with the Darcy seepage characteristics. Moreover, the apparent permeability of samples A and B experience a short period of stability at the initial stage, followed by a gradual decrease until the failure of samples (Figure 8(a) and 8(d). However, the apparent permeability of the samples C, D, E and F exhibit a different variation, where the apparent permeability skips a short period of stability and goes directly into the decrease stage, after that, they even show an increasing trend (Figure 8(c), 8(d), 8(e) and 8(f)). However, the pore pressure does not change significantly when the samples are in failure, with a range from 6.33 MPa to 7.69 MPa. This indicates that the grain composition has a significant effect on the variation in apparent permeability. However, its essential reasons will be further discussed in Sec.4.2.

However, it is interesting that a larger flow rate with 26.84 m/d can flow through the samples F compared to samples C, D, and E with a range from 2.44 m/d to 4.88 m/d. It is explained that the structure of the unconsolidated sandstone with natural gradation is more stable than that of samples with dual grain size. Similar findings are also drawn by Chen et al. (2017).



(a) Sample A (< 0.075 mm + 0.075 ~ 0.25 mm)

(b) Sample B (0.075 ~ 0.25 mm + 0.25 ~ 0.5 mm)

(c) Sample C (0.25 ~ 0.5 mm + 0.5 ~ 1.0 mm)

(d) Sample D (0.5 ~ 1.0mm + 1.0 mm ~ 2.0 mm)

(e) Sample E (1.0 ~ 2.0 mm + 2.0 mm ~ 5.0 mm)

(f) Sample F (Natural Gradation)

Figure 8 Variation in permeability and pore pressure difference for unconsolidated sandstones with DGS: (a) Variation in permeability and pore pressure difference for Sample A with grain composition of <0.075 mm + 0.075 ~ 0.25 mm; (b) Variation in permeability and pore pressure difference for Sample B with grain composition of 0.075 ~ 0.25 mm and 0.25 ~ 0.5 mm; (c) Variation in permeability and pore pressure difference for Sample C with grain composition of 0.25 ~ 0.5 mm and 0.5 ~ 1.0 mm; (d) Variation in permeability and pore pressure difference for Sample D with grain composition of 0.5 ~ 1.0 mm and 1.0 mm ~ 2.0mm; (e) Variation in permeability and pore pressure difference for Sample E with grain composition of 1.0 ~ 2.0 mm and 2.0 mm ~ 5.0 mm; (f) Variation in permeability and pore pressure difference for Sample F with natural gradation.

4. DISCUSSION

4.1 Clogging caused by coupled grain migration and compaction effect

As shown by experimental results in Figure 8, the apparent permeability shows a decreasing trend, and gradually stabilizes and even exhibits a slight increase for the samples C, D, E, and F. Meanwhile, the pore pressure gradually increases with the increasing flow rate until the samples are in failure, as high as 6.33 ~ 7.31 MPa. This indicates that the obvious clogging problem is presented during the seepage experiment. Similarly, the clogging problem has also been observed in the recharge well of GWHP located in Jianghan oilfield, where the recharge pressure was increased from 0.25 MPa to 0.80 MPa, and the recharge rate was dropped to 43% from 85% for 2# recharge well. This further demonstrates that the clogging phenomenon can be reproduced in the laboratory. However, the cause of clogging needs to be further explored in the next work.

Firstly, an obvious diameter shrinkage occurred at the upper of the samples as seen from the damaged samples with different grain compositions after the seepage experiment (Figure 9). Supposed that there is grain migration along the seepage direction. To verify this conjecture, the grain size analysis was conducted for the different parts of samples with dual grain sizes after seepage experiments (Figure 9). The analysis result is given in Table 4. The results of grain size analysis show that the content of fine grain in the upper part of the sample is significantly lower than that in the lower part, please see Figure 10(a), where the fine grain means that all grains with a diameter smaller than the largest original grain size. This effectively proves that the fine grains are migrated from the upper part to the lower part during the seepage experiment. A similar experiment phenomenon was observed in our previous work (Yang et al., 2019), where the variation in apparent permeability with time under constant flow rate for the unconsolidated sandstones was studied. This further demonstrates that the grain migration that occurred in USR located in Jianghan oilfield can be reproduced in the laboratory. Thus, a preliminary conclusion can be drawn that the clogging is related to grain migration during the seepage experiment. Furthermore, the investigation of Dillon et al. (1996) also verified this conclusion, indicating that the clogging can be caused by grain migration during groundwater recharge, which accounts for 5% of cases of clogging according to field surveys.

Besides, it is interesting that the new grain, whose diameter is smaller than the diameter of the original grains, appears in samples B, C, D, and E, as shown in Table 4. Moreover, the content of new grain gradually increases with the increase of original grain size, and the content of new grains in the lower part is significantly higher than that in the upper part, please see Figure 10(b). For this, an acceptable inference can be given. After the original fine grains are migrated from the upper part to the lower part of the sample, space is created by fine-grain migration between the skeletal structure constructed of coarse grains in the upper part of the sample, which has been observed by Yu et al. (2018) in Berea sandstone using 3D micro-CT imaging. Then, the skeletal structure is reconstructed under the compaction effect of confining stress equal to 12.5 MPa. Meanwhile, the stress state of coarse grains is changed due to the structure reconstruction (Zhang et al., 2014), leading to the coarse grains are crushed or even broken into fine grains. A similar conclusion has been drawn by Feda (2002) and Zhang et al. (2014), where coarse sand grains are crushed under high confining stress and increase the finer grains. And, Xiong et al. (2018a) further observed that the coarse grains can be crushed under the coupled effect of high confining stress and pore pressure using the CT scanning technology for the unconsolidated sandstone. Furthermore, as shown in Figure 3, it is seen that the grain size distribution curve of sandstone taken from near 2# recharge well (Location 1) moves toward the left and upward, which indicates the content of the fine grain is significantly increased compared to the sandstone taken from Location 2. This is effective evidence to show that the original coarse grains are crushed into fine grains due to the coupled effect of grain migration and the compaction effect of in-situ stress in the Jianghan oilfield. These results are consistent with those measured and reported in previous studies (Shahnazari et al., 2013; Wu et al., 2018, 2021). It should be pointed out that the fine grains generated by the crushing of coarse grains will also be migrated same as the original fine grains, which can be verified by the fact that the content of new grains in the lower part is significantly higher than that in the upper part, please see Figure 10(b).

Thus, a conclusion is drawn that the clogging is caused by coupled grain migration and compaction effect during seepage experiment. This indicates that the migration of original fine grains and the crushing of coarse grains caused by the compaction effect of in-situ stress are the important reasons for the clogging of the recharge well of GWHP located in Jianghan oilfield. However, it is worth noting that the pores are further filled by the migrated grains for the lower part of the sample, the grains in the pores are denser, and the original skeleton structure constructed of coarse grains is more stable. Meanwhile, the resistance to deformation is strengthened for the lower part of samples. Therefore, the diameter shrinkage occurs in the upper part for the samples with different grain compositions under the compaction effect of high confining stress and pore pressure. This implies that the surface subsidence around the recharge well needs to be monitored considering the long-term coupled effect of grain migration and compaction of in-situ stress. A comparison of the grain migration and the failure mode in the conceptual model is given based on the experimental results and the analysis of grain size, please see Figure 11.

Table 4 The grain content of different parts for the unconsolidated sandstones with dual grain size

Grain Size (mm)	Samples A			Samples B		
	Grain content (%)			Grain content (%)		
	Initial value	Upper part	Lower part	Initial value	Upper part	Lower part
< 0.075	50.00	38.24	55.57	0	1.31	4.24
0.075 ~ 0.25	50.00	61.76	44.43	50.00	36.55	55.21
0.25 ~ 0.5	0	0	0	50.00	62.14	40.55
0.5 ~ 1.0	0	0	0	0	0	0

1.0 ~ 2.0	0	0	0	0	0	0
2.0 ~5.0	0	0	0	0	0	0

Samples C			Samples D			Samples E		
Grain content (%)			Grain content (%)			Grain content (%)		
Initial value	Upper part	Lower part	Initial value	Upper part	Lower part	Initial value	Upper part	Lower part
0	1.05	3.15	0	0.96	4.41	0	1.96	3.29
0	3.41	5.14	0	2.14	3.68	0	3.41	2.15
50.00	32.12	52.55	0	5.42	5.64	0	1.15	6.84
50.00	63.42	39.16	50.00	32.34	48.15	0	7.11	6.34
0	0	0	50.00	59.14	38.12	50.00	33.23	42.13
0	0	0	0	0	0	50.00	53.14	39.25

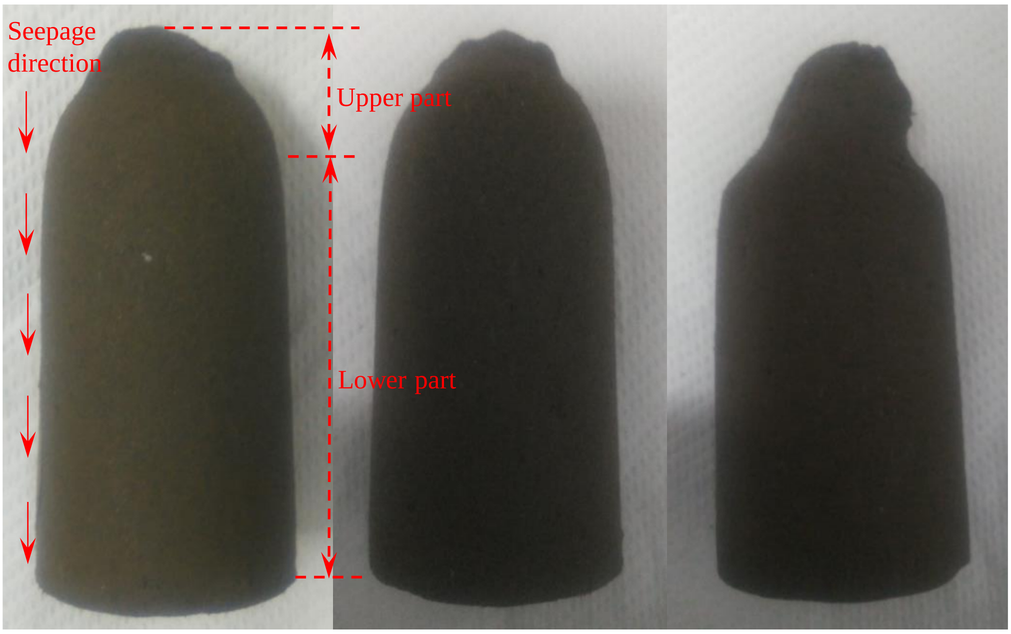
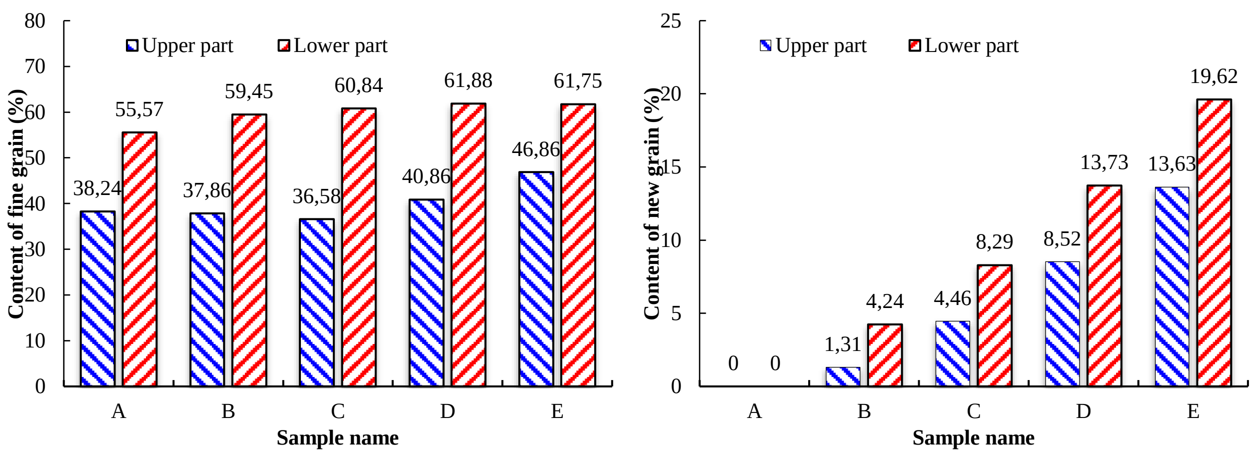


Figure 9 Photos of damaged samples after seepage experiment



(a) Content of fine grain in different part

(b) Content of new grain in different part

Figure 10 Content of fine/new grain in different part for samples with dual grain size

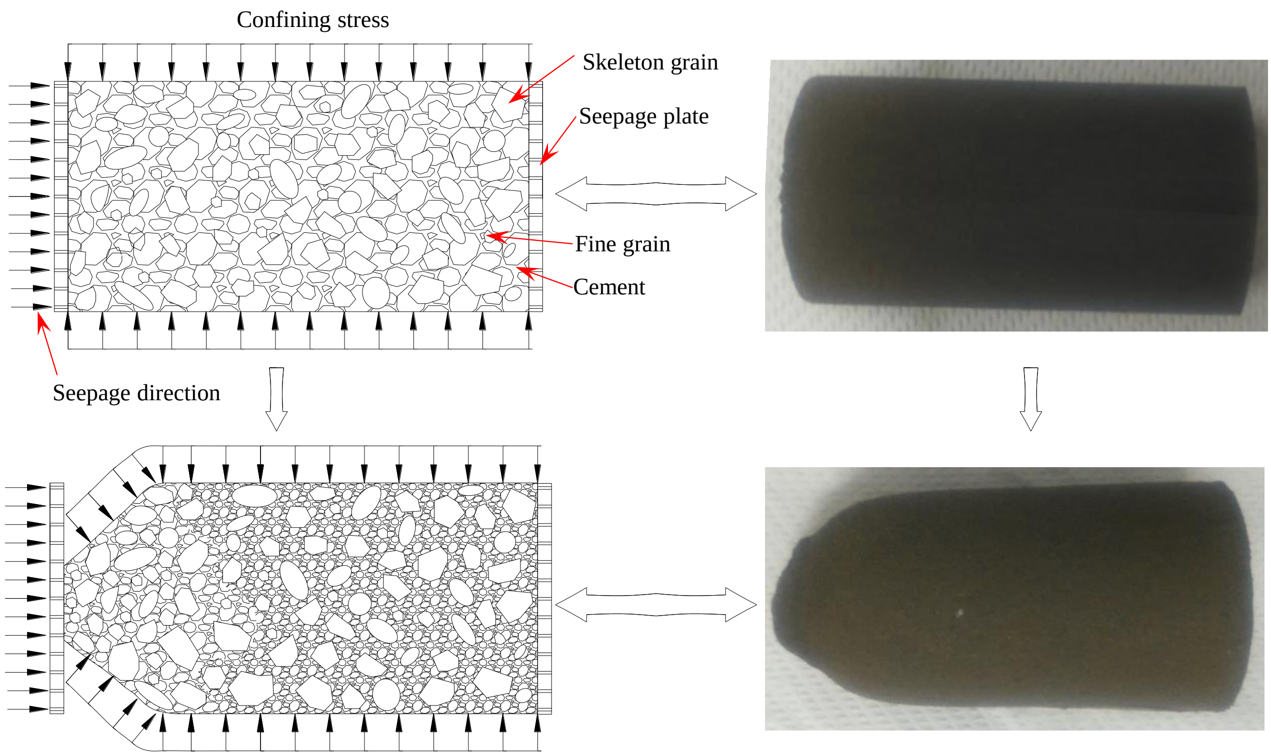


Figure 11 Comparison diagram of the grain migration and the failure mode I in the conceptual model

4.2 Effect of grain composition on grain migration and transportation property

Based on the results of the seepage experiment and the above analysis, a reasonable explanation can be given for the effect of grain composition on grain migration and transportation property. For samples composed of two groups of smaller grain (< 0.5mm), samples A and B, whose apparent permeability first experience a stability stage and then go into a decrease stage. For the stability stage, the pore pressure does not reach the threshold pressure of fine grain at the beginning of the experiment for samples A and B (Richards Reddy, 2012; Van Beek et al., 2014, 2017; Vandenboer et al., 2019), where the fine grains are not migrated, the apparent permeability is stable and the pore pressure continuously increases. In the decrease stage, the fine grains in the upper part of samples are migrated with the increase of pore pressure and block the seepage channel in the lower part of samples, causing a decrease in apparent permeability and a continuous increase in pore pressure.

However, it is interesting that, for the samples composed of two groups of larger grain (> 0.5mm) and the samples with natural gradation, the apparent permeability of samples C, D, E, and F exhibit a different variation compared with that of samples A and B, where both of them skip a stability stage and go directly into a decrease stage, and even that exhibit a slight increase stage. For this, previous studies have shown that the threshold pressure of grain is inversely proportional to grain size (Wang and Qiu, 2017b; Huang et al., 2017). Therefore, the pore pressure reaches the threshold pressure of fine grain at the beginning of experiments for samples C, D, E, and F with larger size grain. An obvious decrease in apparent permeability is exhibited immediately because of the clogging caused by grain migration. Meanwhile, the grains in the pores at the lower part of samples are denser due to the filling of the migrated grains, and the clogging caused by grain migration is more serious. However, with the increase of pore pressure, the grains deposited in the pores of the lower part of the sample are gradually washed out, where the clogging caused by grain migration is dredged. Thus, the apparent permeability exhibits a slight increase. The washing out of grain can be clearly observed from the outlet of the high hydrostatic stress core seepage setup, where the distilled water contains a lot of sand grains. However, it should be pointed out that the washing out of grain promotes the migration of the fine grains and the crushing of coarse grain on the upper part of the sample, leading to the severe deformation under high confining stress and pore pressure, and eventually the sample is destroyed and the experiment is stopped. Therefore, the diameter shrinkage occurs in the upper part of the sample as shown in Figure 9.

In addition, it should be noted that pore pressures as high as 6.33 ~ 7.69 MPa are obtained for all the samples when they are in failure. Actually, the recharge pressure is at a lower level under the condition without clogging (Zheng et al., 2018), with 0.25 MPa in Jianghan oilfield. However, the clogging caused by grain migration is a severe problem during groundwater recharge in Jianghan oilfield. This causes the increase of recharge pressure from 0.25 MPa to 0.80 MPa and the decline of reinjection efficiency from 85% to 43%. Thus, the simulation experiment of the clogging process caused by grain migration was carried out by increasing flow rate under in-situ stress. The initial pore pressures are only 0.095 ~ 0.302 MPa for all samples, whilst the pore pressure as high as 6.33 ~ 7.69 MPa is obtained due to the clogging caused by the coupled effect of grain migration and the compaction of in-situ stress. In addition, a similar phenomenon was also observed by Chang & Zhang, (2013) and Xiong et al. (2018a, 2018b), where the hydraulic gradient of 796 ~ 2 388 kPa/cm was obtained under the confining stress of 30 MPa for cohesive or gravel soil. Of course, effective measures will be taken to reduce recharge pressure in the field, which will be discussed in Sec. 4.3. For example, the results of Dai et al. (2017) indicated that the recharge pressure was reduced from 3.7 MPa to 0.6 MPa for sandstone geothermal reservoirs when the acidification measure was adopted. Nevertheless, the appropriate measures have not been taken to understand the clogging caused by grain migration in the seepage experiment, thus, tremendous pore pressure is exhibited in this work. However, it is interesting that the pore pressure at failure tends to a constant equal to 1/2 of the applied hydrostatic stress for all the samples. This indicates in-situ stress and pore pressure are key factors controlling the failure of USR, and their changes should be monitored in real-time in practices.

4.3 Suggestion for measures in practical engineering

Severe grain migration was observed in USR located in Jianghan oilfield, which is one of the causes of the clogging during groundwater recharge as shown by the experimental results and analysis. Besides, the surface subsidence may occur around the recharge well under the long-term coupled effect of grain migration and compaction effect of in-situ stress, as seen from the failure mode of samples (Figure 9). Thus, effective measures should be taken to prevent the clogging caused by grain migration for USR. Acidification, filter, and well washing are common measures in practices (Guo et al., 2017; Zhang et al., 2020a； Kumar et al. 2021). First, acidification is used to solve the clogging caused by chemical sedimentation, where the acid solution is injected into the recharge well and the reservoir, dissolving the precipitate such as calcium carbonate or other things. The chemical scaling for the recharge wells and fractured rock masses could be solved by acidification, whilst it is not suitable for solving the clogging caused by grain migration and even corroding the wellbore and reservoir. Second, the single or multiple filters are installed in the recharge well or surface purification system (Reddi, et al., 2005), solving the physical clogging caused by the suspended particles in recharge water. Third, the well washing is mainly used to clean the sediment deposition in the well and the fine grains in the filter, including piston washing, pumping water and water injecting, etc. The piston washing through the piston moving up and down in the recharge well, causing violent hydraulic impact, and then cleaning the fine grains on the surface of the filter and the surrounding aquifer. However, the clogging caused by grain migration cannot be solved, and even violent hydraulic impacts will aggravate the grain migration. The washing by injecting water is to install a pipeline in the recharge well, forming a loop with the recharge well. Then, the water is injected into the pipeline and flows out of the loop, thereby achieving the purpose of cleaning the well wall and bottom of the well. However, the clogging caused by grain migration for the USR cannot be solved. The silt and the fine grain in the well could be taken out through the circulation pumping water until clear water flows out, which could repair the damaged reservoir caused by grain migration in certain. However, the repair process takes a long time, and the operation of GWHP is interrupted during the period.

In the Jianghan oilfield, the measures such as reducing extraction flow rate (from 150 m^3/h to 110 m^3/h) and enlarging recharge well diameter (from 177.8 mm to 244.5 mm) have been taken to repair the clogging caused by grain migration for USR. The positive results were presented, where the sand production in the extracted geothermal water is significantly reduced, and the cleaning cycle of the filter is increased from 7 days to 30 days. Surprisingly, the recharge rate has risen from 75% to nearly 99%. However, it is necessary to drill the new pumping well to meet the heating needs of users and retrofit the recharge wells to enlarge their diameter, causing the operation interruption of GWHP and the financial constraints with RMB 5.336 million. It is worth noting that methods that regular alternate injection and extraction of flows in the well could be a potential measure to solve the clogging caused by grain migration in USR. Although it is a common measure in aquifer storage and recovery (Torkzaban et al., 2019), the grains will be transported in reverse under the long-term reverse flow, and the reservoir damage caused by grain migration could be repaired in a recharge well. Meanwhile, it can also achieve the cleaning of the well wall, bottom of the well, and the filter, and even repairing the reservoir damage caused by grain migration in the pumping well. Importantly, the operation of GWHP will not be interrupted. Thus, in the design stage, consideration of the requirements for switching between recharge wells and pumping wells, i.e. double circuit pipeline, pre-set pumps in recharge wells, a suitable distance between the recharge wells and pumping wells, and so on. In the operating stage, an appropriate recharge flow rate is selected to slow down the clogging process caused by grain migration. When the recharge pressure increase sharply or the recharge flow cannot meet the operating requirements, the measure that alternate injection and extraction of flows in the well should be taken (Forghani et al., 2018).

5. CONCLUSIONS

In this work, the clogging caused by the coupled effect of grain migration and compaction of in-situ stress during the groundwater recharge for unconsolidated sandstone reservoirs (URS) is investigated. Taking into consideration that the complication of grain size composition of URS, the effect of grain composition on the grain migration is also considered in this paper. Thus, a series of seepage experiments were conducted by increasing flow rate under in-situ stress for the samples with different grain compositions. The conclusions can be drawn as follows:

(1) Coupled effect of grain migration and the compaction effect of confining stress is one of the important reasons for the recharge clogging in unconsolidated sandstone. Firstly, the original fine grains are migrated along the seepage direction, creating a space between the skeleton structure constructed of coarse grains in the upper part of the sample. Then, the skeletal structure is reconstructed under the compaction effect of confining stress, and the stress field of coarse grains is redistributed, leading to the coarse grains are crushed into fine grains. The migration of original and secondary crushed fine-grain blocks the seepage channel, resulting in the decrease in apparent permeability and the increase in pore pressure.

(2) An obvious threshold of grain size (0.5 mm) is exhibited for grain migration and transportation property. For samples composed of two groups of small grains (< 0.5mm), the fine grains are stable at the initial stage, and then the fine grains are migrated along the seepage direction with increasing pore pressure and block the seepage channel. In consequence, the apparent permeability experiences a transition from stability to decrease. However, for the samples composed of two groups of larger grain (> 0.5mm) and the samples with natural gradation, the fine grains are immediately migrated at the beginning of experiments, and even the grain is washed out, thus, the clogging caused by grain migration is dredged. Therefore, the apparent permeability skips a stability stage and goes directly into the decrease stage, and then exhibits a slight increase.

(3) A unique failure mode, diameter shrinkage in the upper part of the sample, is exhibited under the coupled effect of grain migration and compaction effect of in-situ stress. Pores are created due to the migration of fine grain in the upper part of the sample, whilst the pores in the lower part of the sample are further filled by the migrated grains, enhancing the resistance to deformation. Therefore, diameter shrinkage in the upper part of the sample is presented under the compaction effect of in-situ stress. From a long-term perspective, the surface subsidence around the recharge well in the field needs to be monitored

considering the coupled effect of grain migration and the compaction effect of in-situ stress. Meanwhile, effective measures should be taken to control the grain migration for unconsolidated sandstone reservoirs.

Unfortunately, there are still some technical problems to be solved urgently for simulating the recharging process through laboratory experiments. Firstly, the studied samples are remolded in this paper because the experimental material taken from the field is unconsolidated. Although it is prepared according to the parameters such as water content, density, porosity that are reached in the field, the characteristics of pore structure and the degree of consolidation are different. Secondly, when recharging in the field from the well, the radial velocity decreases exponentially from the well to the formation, whilst the laboratory experiments only reproduce linear flow, not radial. In addition, this work mainly focuses on the clogging caused by the coupled grain migration and the compaction of in-situ stress during the groundwater recharge for USR. The influences of suspended particles, microorganisms, and chemical sedimentation are not considered in this paper. For this, investigation of clogging in consideration of suspended particles, microorganisms, and chemical sedimentation is needed in future works.

ACKNOWLEDGMENTS AND DATA AVAILABILITY STATEMENT

- The data archiving is underway to a data repository of Mendeley Data with URL https://data.mendeley.com/（DOI: https://doi.org/10.17632/442d5z3p66.1）

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

- The financial was supported by the National Key Research and Development Program of China (Grant Nos. 2019YFC0605103 and 2019YFC0605104), National Natural Science Foundation of China (Grant No. 52179114), and Geological Survey Project of China Geological Survey (Grant No. DD20190128).

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