Study on parallel flow diffusion of granular slurry in porous media

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Abstract. The migration velocity model and seepage pressure model of suspension grout with plane-parallel flow state in porous media were proposed based on mass conservation equation, seepage flow continuity equation, linear filtration law, and pressure gradient equations. The effect of the particle filtration process of suspension with distance on the migration velocity, pressure gradient, and seepage pressure was analysed. By using the independently developed monomer combined type osmotic grouting device, the diffusion velocity field and pressure field of cement slurry in sand layer were studied. Then, the value of model test was compared with the filtration theoretical values and without filtration theoretical values. Results show that the difference between the value of migration velocity with neglecting filtration effect and that of the model test was 1.2~17 times. With the decreased of \( \frac{K_c}{K_0} \), the theoretical value and the experimental value of filtration velocity decreased along the path, and the rate of both was positively correlated with the diffusion distance. At a certain diffusion distance, the model test value and the theoretical value of seepage pressure increase with time, but the rate was different. The difference between the model test value of seepage pressure and the theoretical value considering filtration was -23~84kPa, and the deviation rate was -70%~58%. The plane-parallel flow pressure model of slurry can accurately reflect the law of seepage field of cement slurry.

1 Introduction

The 21st century is an era of great development of urban rail transit. So far, 220 cities in 55 countries around the world have operated urban rail transit, and 43 cities in China have
opened 201 rail transit lines (with a total operating mileage of 6,488 kilometers) [1-3]. At present, the design depth of urban rail transit lines is mostly located in the surface shallow layers or sub-shallow layers. However, the distribution area of quaternary sand layer in China is as high as one million square kilometers, so that subway tunnels often pass through the sand layer (especially in riverside and coastal cities) [4-6]. Due to the fragmentation and dispersion of sand layers, which are water-rich and varied in complexity, and the deterioration of groundwater seepage, it is very easy to induce surface subsidence, water gushing, sand bursting and other disasters [7-10] in engineering construction (Table 1). Therefore, if the sand geological disaster can not be effectively controlled in the construction of urban rail transit, it will bring huge safety risks and social burden.

Table 1. Geological hazards and accidents in sand layers.

| Order Number | Time     | Name                  | Disasters and accidents                                                                                                                                 |
|--------------|----------|-----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1            | 2018.02.07 | Foshan Metro Line 2 | Eleven people were confirmed dead, one missing and eight injured in a sand surge accident between Green Island Lake and Lake Surge.                     |
| 2            | 2019.05.27 | Qingdao Metro Line 4 | Five people have been killed after surface subsidence occurred in a Shazikou quiet sandy area.                                                                 |
| 3            | 2019.08.28 | Hangzhou Metro Line 5 | Leakage occurred in the communication channel between Baoshanqiao Station and Jianguo North Road Station, causing road collapse and gas leakage.    |
| 4            | 2019.12.01 | Guangzhou Metro Line 11 | Shahe station collapsed 3 times, the deepest 38 meters, resulting in 3 people lost contact.                                                              |

Due to the limitations of urban composite environment and the dual requirements of strength-impermeability, grouting has become the most commonly used technique for the treatment of soft sand layers. At present, studies on grouting in porous media such as soft sand layer often consider that the slurry uniformly diffuses in the injected medium [11-12]. However, when the cement slurry (suspension slurry) is transported in the sand layer, the medium skeleton will intercept and adsorb the cement particles, resulting in the non-uniform filtration deposition of the cement particles at the diffusion distance, namely the filtration effect [13-14]. Different seepage direction of cement particles will inevitably lead to different filtration quality and pore plugging volume along the process. Compared with the traditional uniform diffusion theory, grouting reinforcement considering the filtration effect will be safer.

So far, plenty of research on the sand layer filtration effect and the diffusion law of suspended slurry has been carried out. Liu Quansheng et al [15] analyzed the deposition characteristics of suspended particles in porous media and established a model of the deposition permeability attenuation of suspended particles in porous media with variable porosity. Cui Xianze et al [16] conducted particle migration-deposition tests at different temperatures and concluded that the higher the temperature is, the lower the peak value of slurry concentration will be. Liu Cheng et al [17] carried out the osmotic film-forming test of sand adding mud in sandy stratum, revealing the plugging mechanism of coarse grain slurry
in the sandy stratum with different pore sizes. Jiang Sichen et al. [18] combined with DLVO theory to analyze the deposition mechanism of suspended particles and concluded that when ion strength is high, spherical particles are mainly deposited in secondary well, while rod-shaped particles are deposited in both primary well and secondary well. Y.S. Yu et al. [19] studied the influences of filter height and particle size on filtration efficiency and fluid performance and concluded that increasing filter height and decreasing particle size are conducive to improving filtration efficiency, but not to reducing pressure slope. Menghuo Chen et al. [20] analyzed the influence of anisotropy on the migration and deposition of nanoparticles by considering the Angle change of seepage field in anisotropic porous media. Zilong Zhou et al. [21] believed that when the mass fractal dimension of porous media is high, the deposition rate of cement particles decreases sharply with the extension of diffusion distance. Binbin Ding et al. [22] proposed a strain-based deep filtration model and studied the lattice type, lattice ratio, and particle capture mechanism of deep filtration. Thomas Carraro et al. [23], Juncheng Qiao et al. [24], Fei Ye et al. [25] studied the empirical equations of effective pressure and permeability of porous media at the outer boundary under the filtration effect. Jenchen Fan et al. [26] analyzed indoor sand column test results according to andorder related index method and stepwise regression method and obtained the influence rules of effective diameter of sand particles and slurry viscosity on grouting time, grouting rate and outflow rate. H. Bayesteh et al. [27] conducted the prototype test of low-moisture clay, discussed in detail the influence rule of grouting technical parameters on the slurry diffusion distance, and revised the existing estimation formula of slurry diffusion distance.

The existing research objects of filtration effect and diffusion theory mostly adopt a single uniform medium and usually ignore the effect of suspended particle shape, pore structure, loading pressure and migration distance on particle deposition, as well as the separation and re-release process of deposited particles. Besides, only the mass difference before and after grouting is calculated in the experiment to obtain the filtration quality of particles, but there are few studies on the velocity field and pressure field variation law of suspension slurry under the filtration effect. Therefore, considering the filtration effect of the soft sand layer, a theoretical model of the velocity field and pressure field of suspension slurry was established in this paper. One-dimensional grouting test was carried out by using the independently developed monomer combined type osmotic device to systematically reveal the transport and diffusion mechanism of suspension slurry. The research results will promote the development of the theory of osmotic grouting and guide the design of on-site grouting.

2 Mathematical model of seepage field
To obtain the filtration effect under the migration rule of cement particles in the medium pore, assumption as follow: lag deposit of cement particles as part of a medium skeleton, strain the cement particles that make up the medium skeleton, the filtration effect can be seen as slurry lose quality of cement particles, medium skeleton obtained the quality of cement particles [28, 29].

According to the mass balance equation, the mass balance equation of cement slurry is

\[-\mu = \frac{\partial (\rho \cdot n_c)}{\partial t} + (\nu_c \cdot \nabla)(\rho \cdot n_c)\]  

(1)

The mass balance equation of the medium skeleton is
\[
\mu = \frac{\partial (\rho_c n_c)}{\partial t} + (v_s \cdot \nabla)(\rho_s n_s)
\]  
(2)

Where, \(\rho_c\) is the density of the cement particle (g/cm\(^3\)); \(\rho_s\) is the density of the medium skeleton (g/cm\(^3\)); \(n_c\) is the volume percentage content of cement particles in unit volume, and is the dimensionalized quantity; \(n_s\) is the volume percentage of the dielectric skeleton in a unit volume, and is the dimensionalized quantity; \(t\) is time (s); \(v_s\) is the velocity of cement particles (cm/s); \(v_c\) is the velocity of medium skeleton (cm/s); \(\mu\) is the mass exchange coefficient, representing the mass of cement particles filtered out of the cement slurry per unit volume in unit time (g cm\(^{-3}\) s\(^{-1}\)).

The cement slurry fills the media pore, and since the filtration effect can be regarded as the mass exchange between the slurry and the medium. So the cement particle density \(\rho_c\) is assumed to be equal to the medium skeleton density \(\rho_s\)\(^{[28-29]}\), and the porosity of the medium is

\[
n = 1 - n_s
\]  
(3)

Where, \(n\) is the porosity of the medium and the dimensionalized quantity.

Equation (2) can be obtained

\[
\frac{\partial}{\partial t} \left[ \rho_c \left(1 - n\right) \right] + 0 = \mu
\]  
(4)

\[
\frac{\partial n}{\partial t} = -\frac{\mu}{\rho_c}
\]  
(5)

According to the law of linear filtration\(^{[28-29]}\)

\[
\frac{\mu}{\rho_c} = -\lambda \frac{n_c}{n_0} = -\lambda \delta
\]  
(6)

\[
\delta(x,t) = \begin{cases} 
1 & (0 \leq x \leq v_f t) \\
\frac{1}{1 + \left(\frac{1}{\varphi} - 1\right) \exp \left(\frac{\lambda x}{n_c v_0}\right)} & (x > v_f t)
\end{cases}
\]  
(7)

Where, \(\lambda\) is the filtration coefficient (s\(^{-1}\)); \(n_0\) is the initial porosity of the medium and the dimensionalized quantity; \(\delta\) is the cement particles content of the slurry in the pore and the dimensionalized quantity; \(\varphi\) is the volume percentage of cement particles; \(x\) is the slurry diffusion distance (cm); \(v_0\) is the initial velocity (cm/s) of cement slurry entering the sand layer.

Equation (6) and (7) can be obtained

\[
n_c = n_c \delta(x,t) = \frac{n_0}{1 + \left(\frac{1}{\varphi} - 1\right) \exp \left(\frac{\lambda x}{n_c v_0}\right)} \quad (0 \leq x \leq v_f t)
\]  
(8)
In the linear element with length $L$ and area $A$, if the pressure at $x = 0$ is the grouting pressure $p_0$, the pressure at $x = L$ is the initial groundwater pressure $p_w$, and the pressure in the cement slurry area be $p$. The initial permeability coefficient of sand injected layer and the permeability coefficient of slurry filtered out deposited layer are $K_0$ and $K_c$ respectively, as shown in figure 1.

![Figure 1. Pressure diagram of plane parallel flow.](image)

The seepage equation and the solution condition of cement slurry are

\[
\begin{align*}
\frac{d^2 p}{dx^2} &= 0 \\
p(x = 0) &= p_0 \\
p(x = L) &= p_w
\end{align*}
\] (9)

According to Equation (9), the pressure distribution in the cement slurry migration area is

\[
p(x) = \frac{(p_w - p_0)x}{L} + p_0
\] (10)

Take the derivative of equation (10)

\[
\frac{\partial p}{\partial x} = \frac{p_w - p_0}{L}
\] (11)

According to Darcy's Law and in combination with Equation (11), the volume flow rate of cement slurry into the sand layer can be calculated as follows

\[
Q = v \cdot A = -k_i A = \frac{K_c (p_0 - p_w)}{\rho_{cs}gL} A
\] (12)

Under the influence of filtration effect, the volume percentage of cement particles occupying the pore space of sand layer is $n_c$, so the effective cross-sectional area of cement particles passing through is

\[
A_c = A \cdot n_c
\] (13)

The flow rate of cement particles is $Q\varphi$, it can be written as,

\[
Q \cdot \varphi = A_c \cdot v
\] (14)

Equation (8), (12) and (13) are substituted into equation (14)
\[ \frac{K_e (p_0 - p_w)}{\rho_{\text{cs}} g L} \cdot A \cdot \varphi = A \cdot n_c \cdot v \]  
(15)

\[ v = \frac{K_e (p_0 - p_w)}{\rho_{\text{cs}} g L} \frac{\varphi}{n_c} \frac{K_e (p_0 - p_w)}{\rho_{\text{cs}} g L} n_0 \exp \left( \frac{\lambda x}{n_0 v_0} \right) \]  
(16)

The pressure drop formula proposed in reference\[28-29\]

\[ \frac{\Delta p'}{\Delta p_0'} = \frac{1}{(1 - j \sigma)^w} \]  
(17)

Where, \( \Delta p' \) is the pressure loss gradient during cement slurry migration (kPa/cm); \( \Delta p_0' \) is the pressure loss gradient in the migration of pure water in sand (kPa/cm); \( \sigma \) is the retention rate, the volume of the retained particles in a unit volume, and the dimensionalized quantity; \( j \) is a scalar, \( m \) is a scalar, and the value range of \( m \times j \) is 28.4 ~ 79.3\[28-29\].

When \( j \sigma \) is small, equation (17) is expanded

\[ \frac{\Delta p'}{\Delta p_0'} = 1 + mj \sigma + \frac{m(m+1)}{2} j^2 \sigma^2 + ... \]  
(18)

Within the sand layer of length \( L \), the volume of filtered cement particles is

\[ \nu t \cdot \varphi = \int_0^t \sigma \, d x \]  
(19)

Where, \( \nu \) is the frontal velocity of cement slurry (cm/s); \( t \) is time (s); \( L \) is the length of sand layer (cm).

Because

\[ p' = \int_0^t dp' = \int_0^t \left( \frac{dp'}{dx} \right) dx = \frac{p_0'}{L} \int_0^t \left( 1 + mj \sigma \right) d x \]  
(20)

Combined equations (19) ~ (20) can be obtained

\[ p' = p_0' \left[ 1 + \frac{mj \varphi \cdot \nu t}{L} \right] \]  
(21)

Where, \( p' \) is the pressure loss on cement slurry front (kPa); \( p_0' \) is the pressure loss (kPa) when the pure water is transported \( L \) in the sand layer.

Substituting Equation (16) into equation (21) can be obtained

\[ p' = p_0' \left[ 1 + \frac{mj \varphi t}{L} \times \frac{K_e (p_0 - p_w)}{\rho_{\text{cs}} g L} \frac{\varphi}{n_c} \frac{K_e (p_0 - p_w)}{\rho_{\text{cs}} g L} n_0 \exp \left( \frac{\lambda x}{n_0 v_0} \right) \right] \]  
(22)

According to the established pressure loss model, the seepage pressure of cement slurry front at different diffusion distances can be obtained, and then the pressure field of cement slurry seepage in sand layer can be obtained.
3 Grouting model test

3.1 Test Materials

The sample was selected from the weak sand layer in Qingdao urban area, and the sand particle analysis test and constant head penetration test were conducted according to the 《Standard for soil test method》 (GBT50123-1999). The sand particle size distribution and structure parameters are shown in Table 2. The cement slurry material is ordinary Portland cement grout (PO42.5) produced by Shandong Shanshui Cement Plant, with \( d_{85}=37 \) μm and \( d_{95}=78 \) μm. The physical properties of the cement paste are shown in Table 3.

| Particle size distribution and structure parameters of sand. |
|--------------------------------------------------------------|
| Sand | 4.75~2.36 | 2.36~1.18 | 1.18~0.60 | 0.60~0.30 | 0.30~0.15 | <0.15 | "K_0/10^2 cm·s^{-1}" | "n_0" |
| S1  | 0  | 163.2 | 327.4 | 1.6 | 1.6 | 6.2 | 3.66 | 0.4 |

Table 3. Functional characteristics of cement paste.

| water-cement ratio | \( \mu \) (mPa·s) | \( \rho \) (g·cm^{-3}) | \( \varphi \) | syneresis rate (%) |
|--------------------|-------------------|-------------------|------|------------------|
| 1:1               | 4.42              | 1.47              | 0.27 | 26.0 |

3.2 Grouting device

The independently developed monomer combined type osmotic grouting device (Figure 2), which is composed of import cabin, single column steel tube, export cabin, full thread compaction pylori, etc. The inner diameter, height, and wall thickness of the single column steel tube are 100 mm, 200 mm and 5 mm, which are splicing of two valves to facilitate the core. The single column steel tubes are nested with each other through the groove, and the sealing ring is added to realize the adjustable length and complete sealing. The inner wall of the steel tube is frosted to eliminate the wall effect.

The grouting pump adopts the continuously variable aerodynamic grouting pump, and the air compressor provides the continuous and stable compressed air to realize the constant flow of cement slurry injection. The Osmotic grouting test system is shown in figure 3.

Figure 2. Monomer combined type osmotic grouting device.
3.3 Parameter design
S1 sand of soft sand layer in Qingdao urban area, the water-cement ratio of cement slurry was set as 1:1, and the seepage field of single cement slurry in sand layer was studied. Formula (23) was used to determine the laminar flow velocity of slurry:

\[ v = \frac{Re \cdot \mu}{\rho_c d_{10}} \]  

(23)

Reynolds number \( Re = 10 \) was the upper limit value of slurry laminar flow, and the effective particle size of S1 sand \( d_{10} = 0.0672 \) cm. When the water-cement mass ratio was 1:1, \( \rho_c = 1.47 \) g/cm\(^3\), and \( \mu = 4.42 \) mPa·s, the upper limit value of laminar flow velocity was \( v_{max} = 4.74 \) cm/s. Considering the parameters of pneumatic grouting pump, the designed constant flow velocity of cement slurry into the sand layer was 0.85 cm/s.

4 Test data and comparative analysis

4.1 Test data and analysis of velocity field
(1) Analysis of theoretical value and experimental value of neglecting the filtration effect
For S1 sand, ordinary Portland cement grout of grade 42.5 was used for grouting, the slurry water cement ratio was 1:1, and the flow velocity in the device was 0.85 cm/s. Figure 4 for the slurry transport velocity and the slurry velocity neglecting the filtration effect in S1 sand.

![Figure 4. Migration velocity curve for ordinary Portland cement grout of grade 42.5.](image-url)
According to figure 4:

1) In S1, the slurry velocity neglected was 0.17 ~ 0.84 cm/s larger than the test value, with a difference of 1.2 ~ 17 times (Multiple=Neglecting the filtration value/Test value). It can be seen that the velocity of parallel laminar flow neglecting the filtration effect was seriously inconsistent with the test value.

2) The rate of slurry migration velocity in each group was different, and the rate of migration velocity was positively correlated with the diffusion distance. For example, S1, the change rate was 3.72×10⁻³ cm/s² at 40 cm, 4.63×10⁻³ cm/s² at 120 cm, and 5.78×10⁻³ cm/s² at 160 cm. The analysis showed that the farther the distance from the feed surface was, the smaller the velocity of the slurry arriving at this position was and the shorter the time until the injection stop. Therefore, the farther the diffusion distance was, the greater the rate of the migration velocity was.

(2) Analysis of theoretical and experimental values considering filtration
When ordinary Portland cement grout of grade 42.5 was used for S1 sand grouting, the calculation parameters were λ=6.5×10⁻³ s⁻¹, n₀=0.42, K₀=3.66×10⁻² cm/s, p₀=22.7 kPa, p_w=0.0 kPa, v₀=0.85 cm/s, ρ_c=1.47 g/cm³, φ=0.27. Set K_c=i×K₀, i=[0, 1]. The calculated parameters were substituted into equation (16) to obtain the theoretical value of slurry migration velocity when the filtration effect was considered. See Figure 5 for the theoretical value and test value when the filtration effect was considered.

![Figure 5. Comparison of theoretical velocity and experimental velocity for S1 sand.](image)

According to figure 5:

1) Under certain conditions, with the constant decreased of the permeability coefficient K_c in the cement slurry area, that was, the constant decrease of K_c/K₀, the migration velocity of cement slurry decreases. The analysis showed that under the filtration effect, the cement particles continuously deviated from the carrier streamline and filter out and stay in the pores of the sand layer, gradually block the pore channel and reduce the permeability coefficient of the sand layer, thus resulting in the poor flow of the slurry and the decline of the migration velocity.

2) The experimental values of each group were in good agreement with the theoretical values considering filtration effect, which showed that the slurry velocity model can
accurately reveal the change rule of the velocity when the cement slurry was in plane-parallel laminar flow under filtration effect.

4.2 Seepage field test data and analysis

(1) Model test data

Osmotic grouting test first before water pressure test was carried out on the S1 sand, measuring the pressure of water migration in the sample loss gradient $\Delta p_0'$. As a result of the grouting pump used for piston, piston reciprocating movement led to monitoring data of volatile, so the pressure loss of water in each sample gradient $\Delta p_0$/average. According to the water pressure test, S1 sand in $\Delta p_0' = 4.85 \times 10^{-2}$ kPa/cm, S1 sand water pressure data as shown in figure 6.

In the grouting test for the parallel flow device of steel tube in S2 sand, the seepage pressure field of the cement slurry at different diffusion distances was monitored by the infiltration pressure sensor and XL2101G static resistance strain gauge. The seepage pressure of cement slurry in S1 sand is shown in Table 4.

![Figure 6. Monitoring value of water pressure test for S1 sand.](image)

**Table 4.** Experimental seepage pressure value of S1 sand.

| Time/s | Seepage pressure at different diffusion distance L (kPa) |
|--------|---------------------------------------------------------|
|        | 40 cm | 80 cm | 120 cm | 160 cm |
| 15     | 18.0  | 38.6  | 55.2   | 58.3   |
| 30     | 65.0  | 102.0 | 83.3   | 62.4   |
| 45     | 144.5 | 131.5 | 123.2  | 65.2   |
| 60     | 159.5 | 158.3 | 141.8  | 72.4   |
| 75     | 163.8 | 172.6 | 153.9  | 87.4   |
| 90     | 183.8 | 185.2 | 171.6  | 123.5  |
| 105    | 187.5 | 188.6 | 180.7  | 146.1  |
| 120    | 198.3 | 190.2 | 187.3  |        |
| 135    | 228.8 | 229.4 | 202.8  |        |
| 150    | 235.8 | 235.0 |        |        |
| 165    | 243.1 | 237.5 |        |        |
| 180    | 261.3 | 246.7 |        |        |
| 195    | 263.5 |        |        |        |
(2) Analysis of theoretical and experimental values considering filtration

Based on the pressure water test had been in the S1 sand $\Delta p_0'=4.85 \times 10^{-2}$ kPa/cm. Meanwhile, according to the research results of IVES [28] and HERZIG [29], the range of $m \times j$ is 28.4~79.3, and its average value was now $m \times j = 53.8$. According to the pressure drop model of plane parallel laminar flow, namely equation (22), the theoretical value of the pressure field during the migration and diffusion of cement slurry in sand sample can be obtained, and the theoretical value of the seepage pressure field was compared with the experimental value, as shown in figure 7.

![Figure 7. Comparison of theoretical and test value of seepage pressure for S1 sand.](image)

The analysis figure 7 shows that:

1) The experimental value of seepage pressure in S1 sand differed from the theoretical value by -23~84 kPa, with a deviation rate of -70%~58% (Deviation rate= (Theoretical value - Test value)/ Theoretical value).

2) After the completion of osmotic grouting, the theoretical and experimental values of seepage pressure in sand decreased along the way. For example, when the injection of S1 sand was stopped, the test value was: the final pressure at 40 cm is 263.5 kPa, at 80 cm was 246.7 kPa, at 120 cm was 202.8 kPa, and at 160 cm was 146.1 kPa.

3) The seepage pressure at a specific diffusion distance increases with time, but the rate of change was different. For example, the early growth rate at 40cm of S1 sand was 3.13 kPa/s, the later growth rate was 0.15 kPa/s, and the average growth rate was 1.36 kPa/s. The growth rate at 120cm was 1.87 kPa/s in the early stage, 1.03 kPa/s in the later stage, and 1.23 kPa/s in the average.

5 Conclusion
(1) Under the specific test conditions, the difference between the migration velocity value of neglected filtration and the model test value was 1.2~17 times, indicating that the neglected filtration effect was not consistent with the actual situation.

(2) With the decrease of $K_c/K_0$, the theoretical value and the experimental value of filtration velocity decreased along the path, and the change rate of both was positively related to the diffusion distance.

(3) The theoretical and experimental values of the seepage pressure in the sand decreased along the way; the seepage pressure at a specific diffusion distance increased with time, but the change rate was different.

(4) The difference between the test value and the theoretical value of the seepage pressure in the sand sample was -23~84 kPa, and the deviation rate was -70%~58%. The results showed that the seepage flow field of cement slurry can be accurately obtained by the pressure model of slurry plane parallel flow and matching the appropriate value of permeability coefficient.

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