Research Article

A New Modified Model of the Streaming Potential Coupling Coefficient Depends on Structural Parameters of Soil-Rock Mixture

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The streaming potential effect in soil-rock mixture (SRM) is related to the compactness and rock content, but there is no model to quantitatively describe this behavior. In this paper, the Kozeny–Carman (KC) equation is modified by using the compactness and rock content. Then, the modified KC equation is substituted into the equation of streaming potential coupling coefficient. A new modified model of streaming potential coupling coefficient that depends on the compactness, rock content, particle shape, and particle gradation is proposed. The reliability of the new modified model is tested by experiments, and the applicable scope of the model is obtained. The results show that when the rock content is 30%, the permeability coefficient prediction accuracy of the modified KC equation is higher in the range of 85–95% compactness. The new modified model of the streaming potential coupling coefficient represents well the control of the compactness (75–95%) on the coupling coefficient. When the compactness remains 85%, the permeability coefficient calculated by the modified KC equation in the range of 10–70% rock content is consistent with the experimental data. The influence of the rock content (10–90%) on the coupling coefficient is well described by the new modified model of the streaming potential coupling coefficient. The new modified model of streaming potential coupling coefficient is helpful to quantitatively evaluate the internal structure evolution of embankment dam by using streaming potential phenomenon.

1. Introduction

Embankment dams play an important role in flood control, irrigation, and power generation. However, the structural aging problem and service life prediction have become the primary concerns of embankment dams in long-term operation. Streaming potential effect is a kind of electrokinetic phenomenon, and the generation process is closely related to the seepage of porous media [1, 2]. It is often used for monitoring of water flow process and has the potential to obtain information on the structure of embankment dams [3]. At present, a large number of studies have been conducted on the streaming potential coupling coefficient model of pure rock and soil. SRM as filling material of embankment dam and the seepage

characteristics of SRM are mainly affected by structural factors such as rock content, compactness, particle shape, and grading curve [4–6]; that means the model of streaming potential coupling coefficient of SRM is different from that of rock and soil. Therefore, the existing streaming potential coupling coefficient model cannot describe the structural characteristics of the SRM.

The issue of the permeability coefficient model of SRM has received considerable critical attention. Xu and Wang [7] point out that the seepage problem of geotechnical media can be solved by means of the heat conduction problem in thermodynamics, and according to the four basic structural models of the thermal conductivity of composite materials (parallel, series, Maxwell-Eucken, and effective medium

theory), the relationship between the permeability coefficient of the SRM and the rock content is obtained (see Table 1). A variety of hybrid structural models are obtained by using the simple combination for the four basic structural models [8]. The series-and-parallel model is developed on the basis of the series model and the parallel model, and the phenomenon that the volume of the SRM will decrease after the fine particles are filled into the pores of the coarse particles is taken into account in this model; then, the model is verified by experiments and shows high accuracy [9]. As shown in Table 1, the relationship between permeability coefficient and rock content has been established in the permeability coefficient model of SRM, but the model does not depend on compactness, particle gradation, and particle shape, and it is difficult to incorporate these structural factors into the model.

The KC equation shows good performance in predicting the permeability of porous media. A large number of scholars have successfully applied the KC equation to the prediction of the permeability of coarse-grained soil [14–16]. Recently, some scholars have extended the scope of application to the permeability prediction of fine-grained soil by substituting the effective porosity into the KC equation [17–19]. Previous studies indicate that the KC equation has the potential to describe the permeability of SRM. The KC equation reveals the relationship among porosity, particle shape, and particle gradation [20]. However, the KC equation is not related to the compactness and rock content. This triggers us to consider establishing the relationship between the KC equation and compaction and rock content through porosity.

The streaming potential coupling coefficient has been the subject of many classic studies in the streaming potential phenomenon. Based on the capillary model, the Helmholtz-Smoluchowski (HS) equation for obtaining streaming potential coupling coefficient is proposed [21, 22]:

$$C = \frac{\varepsilon \zeta}{\mu \sigma_f}, \quad (1)$$

where C (V Pa^{-1}) is the streaming potential coupling coefficient, ε (F m^{-1}) is the dielectric permittivity, μ (Pa s) is the dynamic viscosity, σ_f (S m^{-1}) is the fluid conductivity, and ζ (V) is the zeta potential. The HS equation is valid when the surface conductivity is not considered. The HS equation is independent of the medium structure, so scholars have studied the streaming potential effect of a large number of different porous media materials by using the HS equation [23–26]. Revil et al. [27] derived the analytical solution of zeta potential and specific surface conduction based on the electrochemical reaction at the solid-liquid interface. Glover and Déry [28], Glover et al. [29], and Glover [30] obtained a new modified model by taking the analytical models of zeta potential and surface-specific conductance into the HS equation and studied the evolution of the streaming potential coupling coefficient at different concentrations and pH values. The relationship between the streaming potential coupling coefficient and temperature, concentration, pH, and microstructure (porosity, grain size, and formation factor) was established in the new modified model. As noted above, the HS equation does not

contain any medium structure information, and the new modified model is too complex and includes a large number of parameters, which is not convenient for field application.

Another model for calculating the streaming potential coupling coefficient is derived based on the effective excess charge density, which is dragged by the water flow in the porous medium. Revil and Leroy [31] established a theoretical system that used the effective excess charge density to describe the multifield coupling phenomenon in saturated porous media. The main idea was to extend the local Nernst-Planck and Stokes equations on the representative elementary volume scale to the macroscopic scale by the volume average approach. The streaming potential coupling coefficient was rewritten in the new theoretical system:

$$C = \frac{Q_v k}{\mu \sigma}, \quad (2)$$

where Q_v (C m^{-3}) is the effective excess charge density, k is the permeability (m^2), and σ (S m^{-1}) is the electrical conductivity. This theoretical system was extended to the derivation of multifield coupling governing equations in partially saturated porous media [32, 33]. The same formulation for streaming potential coupling coefficient was obtained in a saturated capillary model by effective excess charge density [34]. The effective excess charge density was used to be calculated by empirical relationship [35, 36]. Guarracino and Jougnot [37] proposed an analytical model of effective excess charge density, which makes the theoretical system more complete. The advantage of Equation (2) compared with the HS equation is that it takes into account the effects of the structure of the medium and surface conductivity [38]. In addition, the permeability is easy to establish relationship with other parameters.

In this work, we propose a new modified model directly relating streaming potential coupling coefficient to the compactness, rock content, particle shape, and particle gradation. The basic idea is to substitute the KC equation improved by compactness and rock content into Equation (2) to obtain a new modified model of streaming potential coupling coefficient. The new modified model is verified via comparison with laboratory data. Our goal in this study is to provide a model that quantitatively explains the effect of the compactness, rock content, particle shape, and particle gradation on the streaming potential coupling coefficient of SRM. This is of great significance to analyze and explain the failure mechanism and health status of embankment dams.

2. Model Development

The model is developed by the following method. We first calculate the porosity of SRM by the parameters of rock content and compactness, then substitute porosity into the KC equation to obtain the relationship between permeability and compaction, rock content, particle gradation, and particle shape, and finally take the permeability into Equation (2) to establish the new modified model of the streaming potential coupling coefficient of SRM.

TABLE 1: The model of permeability coefficient of SRM [7, 8].

Model	Reference	Equation	Notes
Parallel model		$K_{S-RM(p)} = C_S K_S + C_R K_R$	Layered parallel seepage direction
Series model		$K_{S-RM(s)} = \frac{K_S K_R}{C_S K_R + C_R K_S}$	Layered vertical seepage direction
Series-and-parallel model	[9]	$K_{S-RM(SP)} = \frac{n_S^3 (1 - n_S C_S - n_R C_R)^2}{2(n_S C_S + n_R C_R)^3 (1 - n_{S-RM})^2} \left(\frac{K_S K_R}{C_S K_R + C_R K_S} + C_S K_S + C_R K_R \right)$	50% in series and parallel after mixing
M-E model	[10, 11]	$K_{S-RM(ME)} = \frac{K_S C_S + K_R C_R (3K_S / (2K_S + K_R))}{C_S + C_R (3K_S / (2K_S + K_R))}$	One continuous phase and one or more dispersed phases
EMT model	[12, 13]	$C_S \frac{K_S - K_{S-RM(EMT)}}{K_S + 2K_{S-RM(EMT)}} + C_R \frac{K_R - K_{S-RM(EMT)}}{K_R + 2K_{S-RM(EMT)}} = 0$	All phases being mutually dispersed

K_S is the permeability coefficient of soil; K_R is the permeability coefficient of rock. $K_{S-RM(p)}$ is the permeability coefficient of soil and broken rock connected in parallel, $K_{S-RM(s)}$ is the permeability coefficient of soil and broken rock connected in series, $K_{S-RM(SP)}$ is the permeability coefficient of soil and broken rock connected both in series and in parallel, $K_{S-RM(ME)}$ is the permeability coefficient of the Maxwell-Eucken model of SRM, $K_{S-RM(EMT)}$ is the permeability coefficient of effective medium model for SRM, C_S is the percentage of soil volume, C_R is the percentage of rock volume, n_S is the porosity of soil, n_R is the porosity of broken rocks, and n_{S-RM} is the porosity of SRM after blending.

2.1. Permeability Coefficient Model of SRM. We assume that the rock is impermeable and water flows through the pores between fine particles. Figure 1 shows the sketch of three phases of SRM, which is composed of air, water, and solid (rock and soil). We set the volume of solid as $V_s = 1$ (m^3). The void ratio can be expressed by

$$e = \frac{V_v}{V_s} = \frac{V - V_s}{V_s} = \frac{V}{V_s} - 1, \quad (3)$$

where V (m^3) is the total volume of SRM and V_v (m^3) is the total void volume. The total volume of SRM is

$$V = V_s + V_v = 1 + eV_s = 1 + e. \quad (4)$$

The mass of the solid phase can be expressed by

$$m_s = G_s V_s \rho_w = G_s \rho_w, \quad (5)$$

where m_s (kg) is the mass of solid phase, G_s is the specific gravity, and ρ_w ($kg m^{-3}$) is the density of water. Based on the moisture content, it is defined as

$$m_w = w m_s = w G_s \rho_w, \quad (6)$$

where m_w (kg) is the mass of water and w is the moisture content. The total mass of the SRM m (kg) is

$$m = m_s + m_w = (1 + w) G_s \rho_w. \quad (7)$$

Based on Equation (7), we can get another expression of the total volume of SRM:

$$V = \frac{m}{\rho} = \frac{G_s \rho_w (1 + w)}{\rho} = \frac{G_s \rho_w}{\rho_d}, \quad (8)$$

where ρ_d ($kg m^{-3}$) is the dry density of SRM. Combining Equations (4) and (8), another expression of void ratio can be obtained:

$$e = \frac{G_s \rho_w}{\rho_d} - 1. \quad (9)$$

Using $n = e / (1 + e)$ and Equation (9), we obtain

$$n = 1 - \frac{\rho_d}{\rho_w G_s}. \quad (10)$$

According to the geotechnical test standard [39], the average specific gravity of SRM can be calculated by

$$G_s = \frac{1}{(P_1 / G_{s1}) + (P_2 / G_{s2})}, \quad (11)$$

where G_{s1} is the specific gravity of soil particles with a particle size greater than 5 mm, G_{s2} is the specific gravity of soil particles with a particle size less than 5 mm, P_1 is the percentage of the total mass of soil particles with a particle size greater than 5 mm, and P_2 is the percentage of the total mass of soil particles with a particle size less than 5 mm. In this study, the threshold value of soil and rock is referred to the 5 mm adopted by Zhou et al. [9], that is, more than 5 mm is rock and less than 5 mm is soil. The KC equation is developed by Kozeny [40] and Carman [41, 42] and widely used to describe hydraulic conductivity of porous media. The permeability k (m^2) is obtained by the KC equation:

$$k = \frac{1}{C_{K-C}} \frac{1}{S_0^2} \frac{n^3}{(1 - n)^2}, \quad (12)$$

where C_{K-C} is the KC empirical constant, with a value of 5,

FIGURE 1: Three-phase sketch of SRM.

TABLE 2: Design of experimental scheme.

Grouping scheme	Compactness (%)	Rock content (%)
A1–A5	75, 80, 85, 90, 95	30
B1–B5	85	10, 30, 50, 70, 90

A1–A5 represent compactness 75, 80, 85, 90, and 95%. B1–B5 represent rock content 10, 30, 50, 70, and 90%. A3 and B2 are the same conditions.

and S_0 ($\text{mm}^2 \text{mm}^{-3}$) is the specific surface area of particles per unit volume, for uniform spherical particles, $S_0 = 6/D_{\text{eff}}$, and for the nonuniform particles, S_0 needs to be corrected:

$$S_0 = \frac{\text{SF}}{D_{\text{eff}}}, \quad (13)$$

where SF is the shape factor [43]: rounded—6.6; medium angularity—7.5; and angular—8.4. D_{eff} (mm) is the effective particle size and can be calculated by the following equation:

$$D_{\text{eff}} = \frac{100\%}{\sum_i (f_i / (D_{\text{li}}^\alpha \times D_{\text{si}}^{1-\alpha}))}, \quad (14)$$

where f_i is the percentage of particles between the two sieves, D_{li} and D_{si} are the larger and smaller sieve sizes (mm), respectively. For well-graded grain sizes, $\alpha = 0.404$, for poorly graded grain sizes, $\alpha = 0.68$, and for gap-graded grain sizes, $\alpha = 0.9$ [44]. The permeability of the SRM can be obtained by taking Equations (10) and (11) into (12):

$$k = \frac{1}{5} \frac{1}{S_0^2} \frac{[\rho_w G_{s1} G_{s2} - \rho_d (p_1 G_{s2} + p_2 G_{s1})]^3}{\rho_w G_{s1} G_{s2} \rho_d^2 (p_1 G_{s2} + p_2 G_{s1})^2}. \quad (15)$$

Based on the relationship between permeability and permeability coefficient, $K = \rho_w g k / \mu$, the equation for calculating permeability coefficient of SRM can be obtained:

$$K = \frac{\rho_w g}{5\mu} \frac{1}{S_0^2} \frac{[\rho_w G_{s1} G_{s2} - \rho_d (p_1 G_{s2} + p_2 G_{s1})]^3}{\rho_w G_{s1} G_{s2} \rho_d^2 (p_1 G_{s2} + p_2 G_{s1})^2}. \quad (16)$$

2.2. Streaming Potential Coupling Coefficient Model of SRM. Equation (2) has proved to be applicable to porous media with arbitrary structure and multicomponent electrolyte [45, 46]. Therefore, Equation (2) can also be used to calculate the streaming potential coupling coefficient of the SRM. We take Equation (15) into (2) to obtain the modified model of streaming potential coupling coefficient of SRM:

$$C = \frac{1}{5} \frac{Q_v}{\eta \sigma} \frac{1}{S_0^2} \frac{[\rho_w G_{s1} G_{s2} - \rho_d (p_1 G_{s2} + p_2 G_{s1})]^3}{\rho_w G_{s1} G_{s2} \rho_d^2 (p_1 G_{s2} + p_2 G_{s1})^2}. \quad (17)$$

The rock content (the ratio of the mass of the rock to the mass of the SRM is defined as the rock content) and dry density (compactness is equal to the ratio of dry density to maximum dry density) are substituted into the streaming potential coupling coefficient model. It has previously been observed that the effective excess charge density obviously depends on the permeability [47]. According to the empirical relationship, the effective excess charge density can be calculated [35, 36]:

$$\log_{10} Q_v = A_1 + A_2 \log_{10}(k), \quad (18)$$

where A_1 and A_2 are constant values. We will fit these two constants by experimental data. This empirical relationship is widely used to capture water flow information and geometrical properties of media [48–50].

3. Experimental Methods

The experimental scheme is shown in Table 2. We use the self-designed device to measure the potential and water pressure when the brine flow through the SRM. The quality of material is strictly controlled, and the same test procedures are adopted. The specific experimental methodology is described by Zhang et al. [51].

The particle size distribution of SRM material (weathered broken argillaceous rock) is shown in Table 3. The SRM with $C_u \geq 5$ and $C_c = 1 - 3$ is thought to be well graded, if not, the SRM is regarded as poorly graded [52]. So we consider gradations 1 and 5 to be poorly graded, while gradations 2, 3, and 4 are well graded (see Table 4). The particle shape is angular. The X-ray diffraction tests show that the mineralogy of argillaceous rock is composed of quartz (48.8%), illite (22%), albite (17.9%), kaolinite (2.7%), chlorite (5.5%), calcite (1.8%), and hematite (1.2%). The test results indicate that the SRM is silty soil.

Figure 2 shows the new apparatus. The device is mainly composed of a water tank, PVC pipe, and acquisition system. The SRM is compacted in the middle of the water tank. The foam board is placed between the SRM and the upper cover to prevent the water flow. Arrangement of pressure sensors, Ag/AgCl nonpolarized electrodes, and moisture content meters during compaction. The pressure and potential are measured by DH3821 and DM3058, respectively. The saturation of SRM material is monitored by moisture content meters. All experiments are performed at NaCl solution of 0.01 mol L^{-1} .

TABLE 3: Particle size distribution of different gradations.

Particle size (mm)	Gradation 1 (%)	Gradation 2 (%)	Gradation 3 (%)	Gradation 4 (%)	Gradation 5 (%)
<0.075	4	3	2	3	1
<0.25	25	12	10	6	2
<0.5	40	21	16	8	3
<1	55	32	25	10	4
<2	70	48	35	15	5
<5	90	70	50	30	10
<10	98	88	66	58	40
<20	100	100	100	100	100

The particle gradation of A1–A5 is 2. The particle gradation of B1–B5 is 1, 2, 3, 4, and 5, respectively. The minimum sieve size is 0.045 mm.

TABLE 4: Gradation characteristics.

Gradation	d_{60} (mm)	d_{30} (mm)	d_{10} (mm)	Nonuniform coefficient ^a C_u	Curvature coefficient ^b C_c
1	1.3	0.31	0.11	11.82	0.67
2	3.3	0.9	0.2	16.5	1.23
3	8.1	1.5	0.25	32.4	1.11
4	10.5	5	1	10.5	2.38
5	14	8.5	5	2.8	1.03

The d_{10} , d_{30} , and d_{60} denote the particle sizes of 10%, 30%, and 60% of the total mass on the particle size distribution curve, respectively. ^aCalculated from $C_u = d_{60}/d_{10}$ [51]. ^bCalculated from $C_c = d_{30} \cdot d_{30}/d_{10} \cdot d_{60}$ [51].

After the solution on both sides of the water tank is balanced, the static hydraulic head difference H_1 and potential U_1 are measured. The PVC pipe provides hydraulic pressure to the water tank, and the potential U_2 and hydraulic head difference H_2 are measured until the flow state is stable. The streaming potential coupling coefficient is equal to the slope of the fitting line between streaming potential $U_2 - U_1$ and hydraulic head difference $H_2 - H_1$ (see Figure 3(a)). The permeability coefficient is obtained by recording the volume of the solution per unit time. The effective excess charge density is determined by Equation (2). The relationship between effective excess charge density and permeability can be obtained by fitting the experimental data (see Figure 3(b)). We use a two-electrode device to measure the conductivity of SRM. The material properties of SRM are shown in Tables 5 and 6.

4. Results

As shown in Figure 4(a), when the compactness is 75% and 80%, there is a big difference between the predicted values of the modified KC equation and the measured values. When the compactness is greater than 80%, the calculated values of the modified KC equation are close to the measured values. Figure 4(b) shows that there is a big difference between the predicted value and the measured value when the rock content reaches 90%. The predicted value of the modified KC equation is consistent with the measured value in the range of 70% to 10% rock content.

Figure 3(b) shows that the effective excess charge density depends on the permeability of the SRM, consistent with

previous studies [47]. We obtain the coefficient $A_1 = -13.362$ and $A_2 = -1.1197$ in Equation (18), respectively. Some authors have fitted Equation (18), Jardani et al. [35] and Revil [38] obtained $A_1 = -9.23$ and $A_2 = -0.82$, and Bolève et al. [36] suggested $A_1 = -9.9956$ and $A_2 = -0.9022$. We obtain the coefficients are smaller than the fitting results of other authors.

The permeability obtained by the modified KC equation is substituted into Equation (2) to calculate the streaming potential coupling coefficient. Although there is a great difference between measured permeability and predicted permeability at 75–80% compactness and 90% rock content, but the predicted streaming potential coupling coefficient of the new modified model is consistent with the experimental data at different compactness (see Figure 5(a)). Similarly, this new modified model represents the experimental data very well when the rock content varies between 10% and 90% (see Figure 5(b)). Moreover, we use Guarracino and Jougnot's [37] model to calculate the streaming potential coupling coefficient, and the results show that this model reproduces the experimental data very well, but the new modified model is more accurate than Guarracino and Jougnot's [37] model in this study.

5. Discussion

5.1. The Modified KC Equation. At compactness 75% and 80%, the predicted permeability coefficient of the modified KC equation shows poor consistency with the experimental data. The reason for this phenomenon is that the low compactness leads to insufficient bonding of the SRM materials, and the fine particles are loose. When the hydraulic gradient is large, the fine particles are easily carried away, and the flow section becomes larger. Therefore, the measured permeability coefficient is larger than the predicted permeability coefficient. When the compactness is more than 80%, the prediction accuracy of the modified KC equation is higher due to the slight impact on the flow state at high compactness.

In the SRM with 90% rock content, the pore size and the seepage velocity are large, and the fluid is in the state of inertial laminar flow at high water head, so the measured permeability coefficient (apparent permeability coefficient) is smaller than the predicted permeability coefficient [24]. When the rock content is reduced from 70% to 10%, the measured permeability coefficient is closer to the predicted permeability coefficient.

FIGURE 2: Sketch of the experimental apparatus. (a) The apparatus consists of a tank, PVC pipe, and data acquisition system. The blue arrow represents the direction of the water flow. (b) Cross section through the sensor.

This result can be interpreted by the macropores developed between the coarse particles are filled by the fine particles and hence the soil particles are relatively compact and the seepage velocity in the pores is low.

Compactness and rock content are the key parameters in quality management of embankment dam construction. In the project, the compactness is controlled above 90%, and the reference range of rock content is 25–75% [9]. The modified KC equation shows high prediction accuracy of permeability coefficient when the compactness varies between 85% and 95% (30% rock content) and the rock content varies between 10% and 70% (85% compactness). Therefore, the modified KC equation can be considered valid in most projects. The per-

meability coefficient of sandstone–mudstone mixture with a particle size ranges from 60 mm to 0.075 mm is successfully predicted by the KC equation [53]; it appears that the modified KC equation will have a wider application range.

At present, the height of some embankment dams has exceeded 100 meters, and the SRM materials are in complex occurrence conditions of high stress and high water level. It is necessary to establish the relationship between permeability and more parameters, such as effective stress and buried depth, so as to expand the application scope of the model. This means that the physical model for predicting permeability of SRM may become more complex. In recent years, the advantages of artificial intelligence technology in multisource

FIGURE 3: The streaming potential coupling coefficient and the effective excess charge density. (a) The streaming potential against hydraulic head difference at 85% compactness and 30% rock content. The streaming potential coupling coefficient is the slope of the regression line between streaming potential and hydraulic head difference. (b) The effective excess charge density versus permeability. The effective excess charge density is calculated by Equation (2).

TABLE 5: Properties of SRM with different compactness.

Properties	A1	A2	A3	A4	A5
Dry density ρ_d (g cm^{-3})	1.635	1.744	1.835	1.962	2.071
Effective particle size ^a D_{eff} (mm)	0.513	0.513	0.513	0.513	0.513
Specific surface area ^b S_0 ($\text{mm}^2 \text{mm}^{-3}$)	16.361	16.361	16.361	16.361	16.361
Porosity ^c n	0.384	0.343	0.302	0.261	0.220
Conductivity σ (S m^{-1}) $\times 10^{-3}$	1.42	1.36	1.33	1.25	1.20

^aThe D_{eff} is determined from Equation (14). ^bThe S_0 is determined from Equation (13). ^cThe n is determined from Equation (10).

TABLE 6: Properties of SRM with different rock content.

Properties	B1	B2	B3	B4	B5
Dry density ρ_d (g cm^{-3})	1.802	1.853	1.870	1.845	1.870
Effective particle size ^a D_{eff} (mm)	0.387	0.513	0.663	0.961	2.875
Specific surface area ^b S_0 ($\text{mm}^2 \text{mm}^{-3}$)	21.698	16.361	12.676	8.739	2.922
Porosity ^c n	0.321	0.302	0.297	0.308	0.301
Conductivity σ (S m^{-1}) $\times 10^{-3}$	1.35	1.33	1.36	1.45	1.48

^aThe D_{eff} is determined from Equation (14). ^bThe S_0 is determined from Equation (13). ^cThe n is determined from Equation (10).

information fusion and prediction have been rapidly developed, such as predicting the change of coal seam permeability during CO_2 geological sequestration [54] and predicting the permeability of tight carbonate rocks [55]. This provides a new idea for using multiparameters to predict the permeability of SRM.

The modified KC equation as a function of compactness, rock content, particle shape, and grading curve helps us to understand the seepage mechanism of SRM in dam projects

and provides a scientific basis for the design and selection of materials for embankment dams.

5.2. The New Modified Model of the Streaming Potential Coupling Coefficient. The two coefficients are reported by other authors larger than ours. This is because the effective excess charge density and permeability are related to the specific surface area of porous media. The content of coarse particles in the SRM is high and the particle size is large, so

FIGURE 4: The permeability coefficient with different compactness and different rock content. (a) Predicted and measured values of permeability coefficient with different compactness. (b) Predicted and measured values of permeability coefficient with different rock content.

FIGURE 5: The streaming potential coupling coefficient with different compactness and different rock content. (a) Predicted and measured values of the streaming potential coupling coefficient with different compactness. (b) Predicted and measured values of the streaming potential coupling coefficient with different rock content.

the specific surface area is small. This means that the effective excess charge density dragged by the water flow in the pores decreases under the same permeability.

When the compactness is 75–80% and the rock content is 90%, the predicted permeability coefficient is not in good agreement with the measured value, but the predicted streaming potential coupling coefficient is close to the measured value. We ascribe this phenomenon to the relationship

between effective excess charge density and permeability. When the permeability of SRM increases, and the effective excess charge density decreases. It appears that this relationship can improve the difference caused by permeability.

The new modified model shows higher accuracy than Guarracino and Jougnot's [37] model. This result can be explained by the empirical relationship between effective excess charge density and permeability, which is proposed

for specific research objects. The model proposed by Guarra-cino and Jounnot [37] includes the porosity, permeability, tortuosity, concentration, Debye length, and zeta potential, but more influences are considered in the empirical relationship, such as complex chemical reactions on the solid-liquid surface and particle deformation. Nevertheless, Guarra-cino and Jounnot's [37] model still represents the experimental data very well at the different compactness and different rock content.

It should be noted that the zeta potential would not depend on the compactness and rock content of SRM as long as rock mineralogy and chemical composition of water do not change. According to the HS equation, the streaming potential coupling coefficient remains a constant. The change of flow regime leads to the deviation of streaming potential from the HS equation [56]. Therefore, the streaming potential coupling coefficient decrease at low compactness and high rock content.

The relationships between streaming potential coupling coefficient, compactness, rock content, particle shape, and grading curve reported in this study are important for monitoring the structure of embankment dam. At present, the new modified model is rarely used in embankment dams, but Guarra-cino and Jounnot's [37] model has verified the reliability of the new modified model, which lays the foundation for field application. In addition, Bolève et al. [24] and Soueid Ahmed et al. [57] have successfully implemented the numerical simulation of the response of the potential when the leakage path structure changes, which further promotes the application of the new modified model.

6. Conclusion

In this paper, the compactness, rock content, particle shape, and grading curve of the SRM are substituted into the formulation of the streaming potential coupling coefficient by the KC equation, and a new modified model of the streaming potential coupling coefficient depends on structural parameters of SRM is proposed. The modified KC equation and the new modified model of the streaming potential coupling coefficient are verified by the experiment. The main conclusions are as follows:

- (1) Based on the relationship between the porosity, compactness, and rock content of SRM, we obtain the modified KC equation. The modified KC equation fits well with the experimental data and shows high prediction accuracy when the rock content is 30% and compactness ranges from 85% to 95%, and the compactness is 85% and the rock content ranges from 10% to 70%.
- (2) By taking the modified KC equation into the streaming potential coupling coefficient model, the quantitative relationship between the structural parameters of the SRM and the streaming potential coupling coefficient is established. For the rock content remains 30% and compactness varies from 75% to 95%, and the compactness is 85% and the rock content varies from 10% to 90%, the new modified model is in good agreement with the experimental data.
- (3) The modified model of streaming potential coupling coefficient provides a method for studying the mesostructure of the SRM by using the streaming potential effect. It is helpful to reveal and estimate the structural aging mechanism and service life of embankment dams.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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