A framework to determine soil-water retention relation for mine wastes and its applications in emergency risk assessment
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ABSTRACT
Tailing dams and waste dumps formed by the accumulation of mine wastes are usually at long-term unsaturated state under evaporation and consolidated drainage conditions. Soil-water retention relation is one of the key constitutive relations to analyze the seepage processes in tailing dams and waste dumps. In this study, typical coarse- and fine-grained tailings from a metallurgical mine were chosen to study the soil-water retention characteristics of the tailing samples. To begin with, the relationship between volumetric water content and suction of the tailing samples was experimentally measured, and typical soil-water characteristic curves (SWCCs) (i.e., Gardner, van Genuchten and Fredlund–Xing curves) were applied to fit the experimental data. After that, four empirical models to estimate the parameters in SWCCs (i.e., Aubertin-1998 model, Aubertin-2003 model, Vanapalli-2005 model and Chin-2010 model) were tested, and the Vanapalli-2005 model was the best-fit model for the tailing samples. Furthermore, this study proposes a generalized emergency risk assessment soil-water retention characteristics model for tailing dams and waste dumps, and a framework for the quick estimation of parameters in the SWCC is proposed as well. The recommended soil-water retention characteristics model and the related parameters can be used to predict water levels in tailing dams and waste dumps, which are very helpful for emergency risk assessment under rainstorm or flooding conditions.

Key words | emergency risk assessment, mine waste, soil-water characteristic curve, tailing, unsaturated soil

HIGHLIGHTS
- This study is the first study to prove the feasibility of using the Vanapalli-2005 model to estimate parameters in soil-water characteristic curves (SWCCs) for mine wastes.
- This study proposes a framework for the fast determination of SWCCs for mine wastes, which can be used to predict water levels in mine wastes.
- The framework is helpful for the emergency risk assessment of mine wastes under rainstorm and flooding conditions.

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doi: 10.2166/nh.2021.126
INTRODUCTION

Mine wastes are usually stored in two forms: tailing dam and waste dump. In the past 20 years, the number of accidents related to tailing dams and waste dumps substantially increases around the world (e.g., Wang et al. 2011a; Armstrong et al. 2019). Seepage failure is one of the most important failure types to cause accidents (e.g., Rico et al. 2008; Wang et al. 2011a, 2011b, 2012). When a tailing dam is constructed, fine tailing particles need to be mixed with waste rocks from waste dumps before the fine particles can be used to construct the tailing dam. As a result, the cross-scale granular particles coexist in the construction of a tailing dam. In addition, a tailing dam is usually constructed in a ravine, where the upstream catchment area is large. As a result, the complicated seepage in cross-scale granular materials needs to be considered in the hydraulic analysis of the upstream catchment area.

Tailing sands and waste rocks are both typical granular materials with heterogeneity (e.g., Rico et al. 2008). These materials have internal fabrics, in which the skeleton is formed by large particles, and fine particles are filled in the spaces between large particles. In the coarse-grain-dominated layer, the rock fragments make up the skeleton of the packing materials, while in the fine-grain-dominated layer, the skeleton is formed by fine particles.

The packing state and mechanical behavior of tailing dams and waste dumps are greatly affected by hydraulic environments. For example, the solid skeleton can be destroyed by the seepage force under rainfall and water-table fluctuation conditions. Furthermore, the frictional force among the particles may decrease during a seepage flow, which can trigger particle migration and particle rearrangement. Field investigations show that a large area of mine wastes in front of a tailing dam is in an unsaturated state under alternative drying and wetting cycles, and the fully saturated and dry states in waste dumps and tailing dams are rare (e.g., Azam et al. 2007). Hence, the unsaturated characteristics of mine wastes need to be considered in the assessment of hydraulic flow and stability of tailing dams and waste dumps. A soil-water characteristic curve (SWCC) describes the relationship between water content and matric suction, and the SWCC is an important constitutive relation to analyze unsaturated flow and slope stability (Chen & Wei 2016; Chen et al. 2017). A SWCC can also be related to unsaturated permeability coefficient and shear strength (e.g., Rassam & Williams 1999; Lu & Likos 2004). The suction and water content sensors are often used to measure the SWCCs of soils in the field. In the laboratory, the axis transition technique is widely used to determine the SWCCs of unsaturated soils (e.g., Fredlund & Rahardjo 1993). Based on the experimental data, some SWCC models have been developed, such as Gardner’s model, van Genuchten (VG)’s model and Fredlund–Xing (FX)’s model (Gardner 1958; van Genuchten 1980; Fredlund & Xing 1994). Furthermore, alternative approaches to determine the SWCC have also been proposed if there are very limited measured data. For example, the probability function of the particle size distribution is widely used to obtain the SWCC model. In this model, the characteristic parameters of the particle size are used to determine the SWCC parameters (e.g., Aubertin et al. 1998, 2003; Arya et al. 1999; Zhai et al. 2020). To enhance the accuracy of the predicted SWCC model, one SWCC model parameter needs to be calibrated using one measured point, assisted by the characteristic parameters of the particle size (e.g., Vanapalli & Catana 2005; Houston et al. 2006; Chin et al. 2010; Maqsoud et al. 2017). The machine learning method is also used to determine the SWCC model, and typical machine learning approaches include polynomial and neural network models (e.g., Johari et al. 2006, 2011; Saxton & Rawls 2006).

Compared to natural soils, tailings are artificial soil that has different characteristics from natural soil (e.g., Kossoff et al. 2014; Xu et al. 2017). Compared to the sandy soil, the particle size of the grinding tailing soil is much smaller than the one in the natural sands. However, compared to the clayey soils, the bonding behavior of tailings is much weaker due to a lack of clay minerals in tailing soils. Hence, the soil-water retention behavior is expected to be different from the natural soils. Meanwhile, there are two different scales of solid particles in the waste dump: fine-grained soils and coarse-grained rocks (Azam et al. 2007; Xu et al. 2017). There are many large pores in the waste rocks due to the insufficient filling of the fine particles. As a result, the preferential flow and erosion behavior can easily occur for such cross-scale materials. Hence, the unsaturated hydraulic
characteristics of the mine wastes need to be determined and simulated (e.g., Aubertin et al. 1998; Azam et al. 2007). However, there are very limited SWCC data of tailing dams and waste dumps reported in the literature, perhaps due to the time-consuming data acquisition processes. In summary, an appropriate SWCC model for mine tailings and waste rocks has not been developed, and the suitability of existing SWCC models for mine tailings and waste dumps has not been explored. Hence, it is difficult to accurately analyze the evolution of the seepage processes and mechanical behaviors in tailing dams and waste dumps under the changes of water content. It is necessary to explore the suitability of the existing SWCC models for simulating the soil-water retention behavior of the mine wastes. Also, it is important to determine the advantages and disadvantages of the existing SWCC models so as to capture the soil-water retention characteristics of the mine wastes and assess the unsaturated flow and stability behavior of the mine wastes. In addition, to avoid catastrophic mine waste collapse risk, an emergency planning needs to be done during the construction of tailing dams and waste dumps, which includes assessing the site stability and advising prevention measures (e.g., Kossoff et al. 2014). In many cases, there are very limited SWCC data for emergency planning. As a result, it is particularly important to evaluate the seepage flow and site stability of the constructions by using the predicted SWCC model with very limited experimental data.

To explore the above issues related to the SWCC, the SWCCs were first measured using the coarse- and fine-grained tailing samples from a metallurgical mine, respectively. The effects of grain size and compaction on the SWCCs were then explored. The reasons for the discrepancy between measured data and predicted curves were discussed based on the comparison of measured data and fitting SWCCs with three different SWCC models. Furthermore, the existing SWCC models were also used to reproduce the measured data of the cross-scale waste rocks in the literature. The suitability of the developed SWCC models was also explored. At last, a method to determine the appropriate SWCC model was given according to the partition of particle size in a mine waste site. The recommended range of the model parameters was also determined for the purpose of emergency assessment. To validate the reasonability of the SWCC recommendation, a simulated example for unsaturated seepage in a tailing dam was done using the measured and suggested SWCCs. Two key parameters in hydraulic analysis, i.e., the phreatic line and pore pressure, were chosen to validate the developed method in this paper.

**EXPERIMENTAL**

In this paper, seven representative tailing sand samples from metallurgical iron mines were used for the experiments. The samples were taken from the tailings of two iron mines in Shanxi Province, China. The sandy tailings were obtained from magnetic separation at one site. There are two types of tailings from the site, including the tailing coarse sand (>50% of the total mass with a particle size larger than 0.5 mm) and the tailing silty sand (>50% of the total mass with a particle size larger than 0.074 mm). At another site, the flotation process was used to separate the minerals and tailings. The tailings are tailing silty clay, in which <50% of the total mass is with a particle size larger than 0.074 mm, and its plasticity index is 10–17.

**Material properties of tailings**

Table 1 lists the particle size distribution and characteristic parameters of the samples. The particle distribution curve of the sample is shown in Figure 1. From Table 1, the effective particle size \(D_{10}\) and median particle size \(D_{50}\) of the coarse-grained tailing samples (C-1, C-2 and C-3) are larger than 10 times of the fine-grained tailing samples (F-1, F-2, F-3 and F-4).

The influence of dry density on the SWCC of the tailing samples was experimentally explored in this section. A total of seven groups of samples were prepared for coarse- and fine-grained tailings, which include the samples with the in situ dry density of \(1.7 \times 10^3\) kg/m³ and different dry densities, as shown in Table 2.

**Measured SWCCs of tailings**

Combined with the axis translation technique, the pressure plate extractor equipment (from Soil Moisture Ltd) was used to determine the SWCCs of the tailing samples. The ceramic plate with high air-entry values of 3 and 5 bars
was used for coarse- and fine-grained samples in the experiments, respectively. The sample preparation procedures were as follows: first, the dried sample of a certain quantity was weighted, and a small amount of water was sprayed on the sample and was well mixed according to the initial water content. Then, the wet sample was put into a cutting ring (7.0 cm in diameter and 5.2 cm in height) with several layers according to the given dry density. The cutting ring with the sample was fixed into a soil sample saturator. After the saturator was put in a saturation tank for vacuuming for about 4 h, the deionized water was injected into the tank to saturate the tailing sample.

**Table 1**  Percentage by weight (%) of particles with different sizes in samples used in this study

| No. Category | C-1 TCS | C-2 TSS | C-3 TSS | F-1 TSS | F-2 TS | F-3 TSC | F-4 TC |
|--------------|---------|---------|---------|---------|--------|---------|--------|
| 5–2 mm       | 12.8    | 3.3     | 0.0     |         |        |         |        |
| 2–0.5 mm     | 40.7    | 25.4    | 1.7     | –       | –      | –       | –      |
| 0.5–0.25 mm  | 19.2    | 18.7    | 12.3    | 11.20   | 11.20  | –       | –      |
| 0.25–0.075 mm| 13.8    | 28.6    | 65.1    | 45.70   | 19.60  | 10.50   | 6.60   |
| 0.075–0.005 mm| 13.1  | 21.5    | 18.7    | 35.7    | 59.9   | 81.6    | 82.8   |
| <0.005 mm    | 0.4     | 2.5     | 2.2     | 7.40    | 9.30   | 7.90    | 10.60  |
| Cc           | 1.19    | 0.609   | 0.909   | 12.48   | 16.22  | 7.68    | 5.51   |
| Cu           | 14.6    | 5.942   | 2.981   | 1.10    | 1.44   | 2.00    | 1.57   |
| D10 (mm)     | 0.068   | 0.059   | 0.061   | 0.008   | 0.006  | 0.005   | 0.005  |
| D50 (mm)     | 0.285   | 0.112   | 0.099   | 0.060   | 0.035  | 0.050   | 0.012  |
| D95 (mm)     | 0.629   | 0.234   | 0.153   | 0.090   | 0.056  | 0.062   | 0.050  |
| D90 (mm)     | 0.997   | 0.349   | 0.18    | 0.118   | 0.060  | 0.068   | 0.048  |
| D75 (mm)     | 1.366   | 0.483   | 0.209   | 0.152   | 0.065  | 0.079   | 0.056  |
| D50 (mm)     | 3.828   | 1.9     | 0.433   | 0.367   | 0.140  | 0.367   | 0.101  |

TCS, tailing coarse sand; TSS, tailing silty sand; TS, tailing silt; TSC, tailing silty clay; TC, tailing clay; Cc, coefficient of curvature; Cu, uniformity coefficient.

**Figure 1**  Gradation curves for coarse- and fine-grained tailing samples.
The ceramic plate of the pressure plate equipment was also saturated with deionized water by the similar method. The saturated samples were weighted and put on the ceramic plate. The equipment was sealed, and the drying experiment started. The applied steps of matric suction are given in Tables 2 and 3 for coarse- and fine-grained tailings. The equilibrium standard is that the change of the flow-out water content within 24 h is less than 0.2%. After the equilibrium condition was reached at each matric suction, the samples were weighed and the changes of the moisture content of the samples were calculated. The maximum applied matric suction in the experiments was 280 kPa for the coarse-grained tailings and 310 kPa for the fine-grained tailings. After the experiment was finished, the samples were taken out and dried in an oven to determine the final water content of the samples. The dried water content was used to validate the measured water content at each matric suction condition.

### Measured SWCCs of waste rocks

Unlike fine-grained tailings, waste rocks in waste dumps belong to coarse-grained soil. Figure 2 shows the particle size distribution of waste-rock samples in the dump. The particle size distribution characteristics are shown in Table 3. The gradations of samples are well except for the sample W-3, which has a gap-graded particle distribution. Compared to the tailings, there is one order of magnitude difference in the particle size of the waste rock in the dump. The SWCCs of the waste-rock samples were measured by Azam et al. (2007). The maximum applied matric suction is about 100 kPa.

### Table 2 | Particle size distributions of the waste-rock samples

| Sample ID | SW | GP | GW |
|-----------|----|----|----|
| C<sub>c</sub> | 1.2 | 1.1 | 0.6 |
| C<sub>u</sub> | 28.5 | 18.3 | 53.0 |
| D<sub>10</sub> (mm) | 0.2 | 0.4 | 0.2 |
| D<sub>30</sub> (mm) | 1.1 | 1.8 | 1.1 |
| D<sub>50</sub> (mm) | 3.55 | 4.22 | 5.49 |
| D<sub>60</sub> (mm) | 5.7 | 7.3 | 10.6 |
| D<sub>95</sub> (mm) | 32.63 | 39.97 | 44.65 |

SW, well-graded gravelly sand; GP, gap-graded sandy gravel; GW, well-graded sandy gravel.

### Table 3 | Volumetric water contents under different suctions for the coarse-grained tailing samples

| Suction (kPa) | C-1 | C-2 | C-3 |
|---------------|-----|-----|-----|
| ρ<sub>d</sub> (10<sup>3</sup> kg/m<sup>3</sup>) | ρ<sub>θ</sub> - 2.00 | ρ<sub>θ</sub> - 1.70 | ρ<sub>θ</sub> - 1.80 | ρ<sub>θ</sub> - 2.00 |
| 0.1 | 36.5 | 37.68 | 36.21 | 42.46 | 40.56 |
| 5 | 27.42 | 34.33 | 34.29 | 40.81 | 39.94 |
| 10 | 21.95 | 29.64 | 31.63 | 33.68 | 39.61 |
| 15 | 17.53 | 25.41 | 28.86 | 26.03 | 38.01 |
| 25 | 13.24 | 18.36 | 22.88 | 19.36 | 30.49 |
| 30 | 11.87 | 15.3 | 20.54 | 16.99 | 28.36 |
| 45 | 9.92 | 11.17 | 16.10 | 12.38 | 23.41 |
| 50 | 9.6 | 10.42 | 15.20 | 11.76 | 23.68 |
| 80 | 9.29 | 7.72 | 12.91 | 8.74 | 21.27 |
| 120 | 9.06 | 4.72 | 10.56 | 7.95 | 19.68 |
| 200 | 4.97 | 2.56 | 8.78 | 4.42 | 14.10 |
| 280 | 2.63 | 1.46 | 8.84 | 3.39 | 13.87 |

ρ<sub>d</sub>, dry density (10<sup>3</sup> kg/m<sup>3</sup>).

ASSESSMENTS OF THE MEASURED SWCCS

### Measured SWCC data of tailings

The volumetric water content of coarse-grained tailing samples under different matric suctions measured by the pressure plate test is shown in Table 3, and the data of the fine-grained tailings are shown in Table 4. As shown in Tables 3 and 4, the air-entry value of the samples increases with the finer particle size both for coarse-grained tailings (C-1, C-2 and C-3) and fine-grained tailings (F-1, F-2, F-3 and F-4).

In the analysis of engineering seepage, there are commonly used soil-water characteristic models, such as Gardner model, VG model and FX model. For the VG model:

\[
\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (\psi/\alpha)^n]^m}
\]

where \(\theta\), \(\theta_r\) and \(\theta_s\) represent the volumetric moisture content, residual volumetric moisture content and saturated volumetric moisture content, respectively. \(\psi\) is the matrix suction, and \(a\), \(m\) and \(n\) are model fitting parameters.
The FX model is described by the following equations:

\[
\frac{\theta}{\theta_s} = \frac{A}{B}
\]

\[
A = 1 - \frac{\ln (1 + \psi/\psi_r)}{\ln (1 + 10^n/\psi_r)}
\]

\[
B = [\ln (e + (\psi/a)^n)]^m
\]

where \(e\) is the natural base; \(a\), \(m\) and \(n\) are model fitting parameters; and \(\psi_r\) is the residual suction.

The Gardner model is similar to the VG model, using the following equation:

\[
\frac{\theta - \theta_t}{\theta_s - \theta_t} = \frac{1}{1 + (\psi/a)^k}
\]

where \(a\) and \(k\) are model fitting parameters.

The least-squares method is used to fit the experimental data when the three SWCC models are used. The model parameters are shown in Table 5. The determination coefficients \(R^2\) for the Gardner model, the VG

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**Table 4 | Volumetric water contents under different suctions for the fine-grained tailing samples**

| Suction (kPa) | F-1 \(\rho_d = 2.00\) | F-2 \(\rho_d = 2.00\) | F-3 \(\rho_d = 1.85\) | F-3 \(\rho_d = 1.95\) | F-3 \(\rho_d = 2.00\) | F-3 \(\rho_d = 2.05\) | F-4 \(\rho_d = 2.00\) |
|--------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0            | 13.47           | 16.64           | 21.31           | 18.54           | 18.32           | 16.09           | 16.64           |
| 4            | 8.77            | 12.69           | 16.69           | 14.81           | 14.25           | 13.76           | 12.69           |
| 12.8         | 4.95            | 7.31            | 10.75           | 9.03            | 7.78            | 8.71            | 7.31            |
| 25           | 3.95            | 5.38            | 8.19            | 7.34            | 5.91            | 6.9             | 5.38            |
| 38           | 2.99            | 4.14            | 7.1             | 6.26            | 4.67            | 5.86            | 4.14            |
| 82           | 1.72            | 2.06            | 4.25            | 4.01            | 2.25            | 3.97            | 2.06            |
| 140          | 0.76            | 1.01            | 3.17            | 3.17            | 1.35            | 3.01            | 1.01            |
| 310          | 0.25            | 0.59            | 2.81            | 2.73            | 0.81            | 2.61            | 0.59            |

\(\rho_d\), dry density (10^3 kg/m^3).
model and the FX model are all greater than 0.98. The well consistency between the measured data and the fitted curves indicates that (1) the SWCC fitting models summarized in the literature are suitable for describing tailing SWCCs and (2) the fitting accuracy can be met no matter whether the tailings are coarse or fine, and the fitting accuracy is satisfactory given different tailing densities. Therefore, in practice, on the basis of calibrating the model fitting parameters, the aforementioned SWCC models can be chosen for the seepage analysis of tailings.

Given the fact that the determination coefficient $R^2$ of all fitting models meets the requirements, the following analysis and discussion are based only on the fitting curves from the FX model, and the analysis and discussion are expected to be applicable to other models as well.

### SWCC characteristics of tailings

#### Relationship between volumetric water content and matric suction

Figure 3(a) shows a comparison between the measured and fitted tailing SWCCs using the FX model with different particle sizes and the same dry density ($2.0 \times 10^3$ kg/m$^3$). It can be seen that the relationship between the volumetric water content and the matrix suction of the three samples had the standard S-type for coarse-grained tailings. Due to the difference in particle gradation, the air-entry value and the residual water content of the samples were different. The air-entry value and the residual moisture content of the samples were perhaps related to the content with the particle size of 0.25–0.075 mm. Among the three samples, C-3 had the largest content (65.1%), and C-1 had the smallest content (13.8%). As the content of the 0.25–0.075 mm particle group increased, the air-entry value, water-entry value and residual volume water content all increased on a semi-logarithmic coordinate. Chen & Uchimura (2016) showed that the air-entry value and residual water content were related to the effective particle size $D_{10}$ of the soil. However, this study shows that $D_{10}$ had no correlation with air-entry value and residual moisture content.
moisture content (C-1, C-2 and C-3 were almost the same). Interestingly, from the analysis of the particle size distribution characteristics in Table 1, the air-entry value and residual water content were closely related to the unevenness coefficient $C_u$ ($C_u = D_{60}/D_{10}$) of the three samples, and the $C_u$ values were 14.60, 5.942 and 2.981 for the three samples, respectively.

Figure 3 | Measured and fitted SWCCs for the coarse-grained tailing samples (a) and the fine-grained tailing samples (b) with the same dry density.

The water retention capacity of a soil is not only related to the particle size distribution but also directly related to the pore size and pore distribution in the soil. On the one hand, when the soil material is given, the matric suction during the drying processes of the soil depends on the size and number of pores in the soil. According to the Young–Laplace equation, the matric suction is related to the

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equivalent pore size. Under the given matric suction, the pores smaller than the equivalent pore size are filled with water, and pores larger than the equivalent pore size lose water. On the other hand, the size of the soil particle is related to the mineral compositions of the soil. The matric suction is larger under the same water content when the particle becomes finer, and the contact angle is smaller. Our test confirmed the aforementioned implications from the Young–Laplace equation: the mean particle diameter $D_{50}$ of C-1, C-2, and C-3 decreased in sequence, as shown in Table 1. The matric suction of the samples sequentially increased under the same water content condition. Furthermore, the measured and fitted SWCCs of the fine-grained tailings with the same dry density are given in Figure 3(b). The trend of the SWCCs for the fine-grained tailings is similar to the one for the coarse-grained tailings.

It is worth noting that the residual water content of different fine tailing samples is close, and the statistical $D_{10}$ is also close. Compared to the fine-grained tailing, the slope of the SWCC curve becomes steeper when the particle changes from coarse to fine. Under the same matric suction force, the water content of the sample increases with the decrease of the particle size, showing an enhanced water retention capacity. From the perspective of the stability of the tailing dam, the pore pressure cannot dissipate in time in fine-grained tailings, which decreases the strength of solid skeleton and increases the safety risk during dam construction. To avoid this risk, waste dumps are usually used to build dams, such as Yuanjiacun Iron Mine (Wang et al. 2012, 2015).

**Effect of dry density on SWCCs**

Under certain conditions of gradation and soil properties, the dry density characterizes the compactness of the sample. For the tailing dam, the dry density is controlled by the dam construction technology (swirl damming or layered rolling) and is also affected by the self-weight consolidation. For the dump, the density is affected by the self-weight consolidation. However, the orientation of internal stratification waste is affected by particle separation during material falling in the dumping of waste rock. Under this situation, the permeability of the waste rock is usually anisotropic.

Figure 4 shows the experimental results of the coarse-grained tailing samples C-2 and C-3 and fine-grained tailing sample F-3 under different dry densities. The fitted curves from the FX model are also shown in Figure 4. It can be seen that the slope of the SWCC becomes lower as the dry density increases. The discharge volume in the tailings becomes smaller when the dry density increases. The results also show that the residual water content increases for coarse-grained tailings, and the residual water content reaches the same value for fine-grained tailings. Compared to C-2, the increase in the air-entry value and the residual water content of C-3 are more obvious. Based on the microscopic mechanism, the fine particle content has a great effect on the water retention characteristics of the soil. The water retention capacity can increase when the fine particle content increases in soil. Among the three coarse-grained samples, the fine particle content of the sample C-3 is the highest, as shown in Figure 1. Furthermore, the difference in residual water content for fine-grained tailings with increasing dry density is limited. The results show that there is a threshold pore size (lower limit). The residual water content is no longer affected by the density when the threshold pore size reaches during a drying process.

**SWCC characteristics of dumping materials**

This section explores the suitability of the existing SWCC models to describe the soil-water characteristics of waste rocks with substantially varied grain sizes. The three SWCC models are used to fit the measured data from Azam et al. (2007). The key parameters for the SWCC of waste rocks are listed in Table 6. The fitting parameters from different SWCC models are listed in Table 7. Except for a low determination coefficient for the sample W-5 by the Gardner model, the determination coefficient by the three models is greater than 0.96. The comparison between the measured and fitted SWCCs by the FX model is shown in Figure 5. The results show that the fitting SWCC models are suitable to describe the soil-water characteristics of the waste rock.

The SWCC shape of the waste-rock sample is different from the single S-shape of the tailing sample. The SWCC curve includes inverted L-shape, nearly straight line, and normal L-shape. Unlike the SWCC of tailings, the change in the SWCC shape of waste rocks is not closely related to the particle size characteristic parameters, such as particle size and unevenness coefficient.
The bulk of the waste dump spans two scales of fine-grained soil (silt and sand) and coarse-grained rock (gravel and block stone). Rolling, shear flow and breakage of the particles can occur during the construction of the dump. Due to insufficient filling of fine particles, there are usually many pores between large waste-rock particles. As a result, the matrix flow and the large pore flow in the waste dump can coexist, showing the characteristics of preferential flow which may be related to the cross-scale phenomenon of bulk particle size in the dump. It is worth noting that the decline rate of the water content in drainage processes of samples W-4 and W-5 is much higher than that of samples W-1, W-2 and W-3. Due to the low water retention capacity, the internal structure supported by the fragments in samples W-4 and W-5 drained quickly. The behavior can provide guidance to enhance the drainage capacity when the fine-grained tailings are used to construct dams. For example, vertical drainage well–horizontal drainage blind ditch combined measures can be used to enhance the drainage capacity of the tailing dam.

Table 6 | Key characteristic parameters of the SWCC model for selected waste-rock samples

| Sample ID | Saturated volumetric water content (θs) | Air-entry value (ψa, kPa) | Residual volumetric water content (θr) | Residual matric suction (ψr, kPa) |
|-----------|----------------------------------------|---------------------------|----------------------------------------|----------------------------------|
| W-1       | 0.31                                   | 3.42                      | 0.14                                   | 39.80                            |
| W-2       | 0.30                                   | 2.56                      | 0.19                                   | 21.54                            |
| W-3       | 0.22                                   | 3.10                      | 0.12                                   | 40.06                            |
| W-4       | 0.29                                   | 0.16                      | 0.14                                   | 9.62                             |
| W-5       | 0.54                                   | 0.02                      | 0.15                                   | 0.38                             |

Figure 4 | SWCCs of the coarse-grained sample C-2 (a), C-3 (b) and F-3 (c) with different dry densities.
Suitability of the fitting SWCC models for mine waste

Different from the fixed structural configuration of the earth-rock dams or engineering slopes, the tailing dams or dumps are often in continuous construction and operation. Controlled by the damming process, the cyclone dam construction or layered roller compaction and stacking are often used. The strong characteristics of spatio-temporal variation are shown in the tailing dams. Due to the effect of particle sorting, the tailings have a high coarse-grain content near to the dam. In addition, the content of fine-grained particles increases in the area away from the dam. Furthermore, the deep and early discharge of tailings continues to be consolidated during the height increase of the tailing dam year by year, or in the end-dump stacking process of the dump. In addition, the fine-grained particle compaction

Table 7 | Different SWCC models and fitting parameters for selected waste-rock samples

| Model | Fitting parameters | W-1 | W-2 | W-3 | W-4 | W-5 |
|-------|-------------------|-----|-----|-----|-----|-----|
| Gardner | $a$ | 14.527 | 9.151 | 12.009 | 0.902 | 0.088 |
| | $k$ | 1.809 | 1.666 | 1.310 | 0.533 | 0.590 |
| | $R^2$ | 0.9973 | 0.9852 | 0.9788 | 0.968 | 0.8470 |
| VG | $a$ | 1,756.114 | 25.244 | 145,706.245 | 121.445 | 0.009 |
| | $m$ | 284.928 | 2.693 | 5,633.526 | 4.874 | 0.004 |
| | $n$ | 1.324 | 1.308 | 0.965 | 0.393 | 84.074 |
| | $R^2$ | 0.9983 | 0.9863 | 0.9906 | 0.9729 | 0.9573 |
| FX | $a$ | 7.341 | 3.764 | 7.095 | 0.147 | 0.015 |
| | $m$ | 0.582 | 0.315 | 0.675 | 0.770 | 0.304 |
| | $n$ | 2.069 | 2.225 | 1.077 | 0.532 | 7.164 |
| | $R^2$ | 0.9987 | 0.9813 | 0.9872 | 0.9805 | 0.9925 |

Figure 5 | Measured and fitted SWCCs of the waste-rock samples.
areas under the effect of the transport machinery often appear on the top of the dump. The density and porosity change in different depths and areas due to the special technique on the tailing dam and waste dump. Therefore, the divisional and layered characteristics in the particle size should be considered in the seepage analysis under the damming process, which has great important effects on the establishment and selection of SWCC models.

In summary, the fitting SWCC models developed for natural soils are suitable for describing the soil-water retention behavior of mine wastes, including tailings and waste rocks in dumps. Our experimental studies reveal that the difference in dry density and the content of key granule groups substantially affect the characteristics of the SWCCs. Therefore, in the analysis of seepage stability, the effects of the different dry density and the content of the particle group on the SWCC should be considered caused by consolidation age in different areas of the tailing pond and particle sorting. It is recommended that the spatio-temporal characteristics need to be considered in the simulation strategy. In the horizontal direction, the model can be developed based on the divisional regions according to the particle size. In the vertical direction, the SWCC values are assigned in layers based on the stacking age of the tailings.

**PREDICTION OF SWCC PARAMETERS**

As mentioned earlier, SWCC measurements are extremely time-consuming. Currently, the SWCC data of mine tailing dams and dumps are very limited. In particular, emergency management often requires urgent decision made in time. It is very helpful in urgent response if the basic shape and the parameters of the SWCC can be swiftly and conveniently estimated. Therefore, this study further explores the suitability of the four SWCC parameter prediction models (i.e., Aubertin et al. 1998, 2003; Vanapalli & Catana 2005; Chin et al. 2010) on mine waste materials. The comparison between the four predicted models and the VG and FX models to describe the soil-water behavior of mine wastes has been done. Also, the discrepancy between the predicted and measured SWCCs is discussed. The recommendations are given regarding the selection of the prediction models, which can offer guidance for the analysis of unsaturated seepage and slope stability for tailing dams and waste mine dumps.

**Overview of the prediction models**

**Aubertin-1998 model**

This model is specifically established to predict the SWCC of the tailings (Aubertin et al. 1998). The model is described by the following equations:

\[ \theta = n[S_c + S_a(1 - S_c)] \]  
\[ S_c = 1 - \left( \frac{h_{co}}{\psi} \right)^2 + 1 \exp \left( -m \left( \frac{h_{co}}{\psi} \right)^2 \right) \]  
\[ S_a = C_\psi \frac{a}{e^{\psi_90}} \]  
\[ C_\psi = 1 - \frac{\ln \left( 1 + \frac{\psi}{\psi_r} \right)}{\ln \left( 1 + \frac{\psi_0}{\psi_r} \right)} \]  
\[ h_{co} = \psi_90 = \frac{b}{eD_{10}} \]

where \( n \) is the porosity; \( S_c \) depends on the capillary force; \( S_a \) depends on the adhesion; \( h_{co} \) represents the height of capillary rise of water, expressed in centimeter head; \( \psi_90 \) is the estimated air-entry value; \( e \) is the porosity ratio; \( D_{10} \) (mm) is the particle size value with a mass fraction less than 10%; \( b \) is an empirical value of the estimated air-entry value, and an empirical value of 4.0 mm is used. \( \psi_0 \) is 10 cm water column. \( \psi_r \) is 1.5 \times 10^4 cm water column, which is an empirical value. \( a \) and \( m \) are two empirical values as well, and this study uses an \( a \) value of 0.006 and an \( m \) value of 0.05.

**Aubertin-2003 model**

To reflect the difference in unsaturated properties of granular soils with a liquid limit of less than 30% and clayey plastic soils with a liquid limit of more than 30%, Aubertin et al. (2003) proposed a new SWCC model and was adopted by the commercial program GeoStudio. Liang et al. (2015)
also used this model to predict a set of SWCCs of coarse-grained soil. The following equations were developed to replace the Equations (6) and (8) in the Aubertin-2003 model:

$$\theta = n[1 - (1 - S_n)(1 - S_c)]$$

(11)

$$S_a = \frac{a_c \psi}{\psi_{r}} \frac{\left( \frac{h}{\psi} \right)}{\left( \frac{w}{\psi} \right)^{\frac{1}{2}}}$$

(12)

where \(\langle \rangle\) is an operator and \(\langle x \rangle = 0.5(x + |x|)\). \(\psi_n\) is the parameter for dimensionless, if \(h_{co}\) expresses in centimeters of water column, then \(\psi_r = 1\). \(a_c\) is an empirical parameter, which takes 0.01 for granular soil and \(7 \times 10^{-4}\) for clayey plastic soil. \(m\) is an empirical parameter, which takes \(1/C_u\) for granular soil and \(3 \times 10^{-5}\) for clayey plastic soil. \(h_{co}\) and \(\psi_r\) are related to the type of soil. For granular soils, Equations (13) and (14) are used for calculating \(h_{co}\) and \(\psi_r\); for clayey plastic soil, Equations (15) and (16) are used for calculating \(h_{co}\) and \(\psi_r\):

$$h_{co} = \frac{1}{e}D_{10} \left( 0.75 \right) \frac{0.17 \log(C_u) + 1}{1}$$

(13)

$$\psi_r = 0.86h_{co}^{1.2}$$

(14)

$$h_{co} = \frac{0.15}{e} \rho_s w_{L}^{1.45}$$

(15)

$$\psi_r = 0.86 \left( \frac{0.15}{e} \rho_s \right)^{1.2} w_{L}^{1.74}$$

(16)

where \(\rho_s\) is the particle density, and \(w_L\) is the liquid limit expressed as a percentage.

Vanapalli-Catana-2005 model

The Vanapalli-Catana-2005 model has the same form as the FX model, namely Equations (2)–(4), but has a new fitting parameter \(x\). The parameters are shown in Equations (17)–(20) (Vanapalli & Catana 2005). By measuring a single point on the SWCC to predict the entire curve, it saves a great deal of time than a complete experiment:

$$a = 1.33 \left( \frac{e}{x_{0.86}} \right)^{A}$$

(17)

$$m = x$$

(18)

$$n = \frac{7.78}{(C_u \cdot e)^{1.14}}$$

(19)

$$\frac{1}{d_c} = \sum_{i=1}^{n} \frac{\ln \left( \frac{d_i}{d_{ci}} \right)}{d_i - d_{ci}}$$

(20)

where \(d_c\) is the characteristic particle size in millimeters. \(\Delta g_i\) is the mass fraction of particles in a specific particle size range. \(d_{ci}\) is the largest particle size in a certain particle size range. \(d_{ci}\) is the smallest particle size within a certain particle size range. \(x\) is the fitting parameter.

Chin-2010 model

The Chin-2010 model also uses the form of the FX model, combined with a single-point measurement method to give the entire curve (Chin et al. 2010). The difference between the Chin-2010 model and the Vanapalli-Catana-2005 is that the Chin-2010 model uses the mass percentage of the sample\(P_{200}\), passing through a 200-mesh sieve (particle size: 0.075 mm), as an indicator to distinguish the samples. For \(P_{200}\) in the samples greater than or equal to 30%, the parameters are calculated using Equations (21) and (22). For \(P_{200}\) in the samples less than 30%, the parameters are calculated using Equations (25)–(28).

$$a = -2.4x + 722$$

(21)

$$m = 0.015x^{0.7}$$

(22)

$$n = 0.07x^{0.4}$$

(23)

$$\psi_r = 914e^{-0.002x}$$

(24)

$$a = 0.53D_{20}^{0.96}$$

(25)

$$m = -0.23 \ln (x) + 1.13$$

(26)

$$n = x$$

(27)

$$\psi_r = 100 \text{kPa}$$

(28)
where $D_{50}$ is the particle size value whose mass fraction is less than 50%, and $x$ is the fitting parameter.

Theoretically, the more physical indicators used in the model, and the predicted model can give much closer predicted curves to the measured data. Table 8 lists the physical properties used directly or indirectly by the above SWCC models. The Chin-2010 model equation uses only one indicator, and the prediction accuracy fluctuates greatly, depending on the choice of the calibration point. Although the Aubertin model uses three indicators, the curve shape is close to the actual measurement result in the partial suction range. The Vanapalli-Catana-2005 model also uses three indicators, but the calculation of its characteristic particle size requires the entire particle curve. The actual information contained is much larger than other models, plus a fitting point; in fact, the most used the physical property indexes.

Suitability evaluation of the prediction models

Evaluation of the prediction models for the tailings

The particle size distribution characteristics (Table 1) show that there are two types of tested samples: coarse-grained tailings (C-1 to C-3 and F-1) and fine-grained tailings (F-2 to F-4). For C-1 to C-3 and F-1, the model adopts the equation suitable for granular soil, because C-1 to C-3 and F-1 are granular soils. The Aubertin-2003 model uses Equations (13) and (14), and the Chin-2010 model uses Equations (21)–(24). Correspondingly, for F-2 to F-4, the equation suitable for plastic clay needs to be used. Hence, the Aubertin-2003 model uses Equations (15) and (16), and the Chin-2010 model uses Equations (25) and (26) for F-2 and F-4.

The comparison between the experimental and predicted results of the SWCCs of different samples is shown in Figure 6. Overall, the predicted values of the one-point models are close to the experimental data. However, the prediction results from the Aubertin-1998 and Aubertin-2003 models both deviate from the measured values. The prediction curves are on the left side of the measured curve, shifting to the low suction range. At the same time, the predicted air-entry value is lower than the measured value. From the shape of the curve, the suction range of the descending section is narrower, showing that the slope of the predicted curve is larger than the measured curve.

Furthermore, Figure 6 shows that the Chin-2010 model yields a better parameter prediction for the SWCC than the Aubertin model for the tailing sand used in this study. Xu et al. (2017) also reach the same conclusion. In some cases, the predicted results from the Chin-2010 model are even better than the results from the Vanapalli-Catana-2005 model.

Evaluation of the prediction models for the dumping material

As shown in Figure 7, the predicted results using the one-point method (Chin-2010) match the measured SWCCs from Galla et al. (2008) well for both drying and wetting conditions. In Galla et al. (2008), the dumping materials have a uniformity coefficient ($C_u$) of 406.30, and the Chin-2010 model has the best performance compared with other models under the given conditions.

However, all the four prediction models cannot give reasonably predicted parameters for the SWCCs of the dumping materials in Azam et al. (2007). The predicted curves greatly deviate from the measured data reported by Azam et al. (2007), and the discrepancy may be related to the particle size curve. The threshold particle size (e.g., 4.75 mm) separating the waste rock in the dump and the coarse-grained tailings contribute to the fact that the SWCC prediction does not apply to the gravel part in the particle size distribution curve. As a result, only the fine particle part is needed to obtain the key parameters of the SWCC curve, such as $C_u$, $e$ and $d_e$. In summary, the influence of the relative abundance of the two-particle groups on the overall hydraulic properties of the dump materials needs to be considered.

Table 8 | Indices used in the SWCC parameter prediction models

| Model                              | Void ratio | $D_{10}$ (mm) | $C_u$  | Liquid limit | Other parameters |
|------------------------------------|------------|---------------|--------|--------------|------------------|
| Aubertin-1998                      | √          |               |        |              |                  |
| Aubertin-2003 (granular soil)      | √          |               |        |              |                  |
| Aubertin-2003 (plastic clay)       | √          |               | √      |              | Specific gravity |
| Vanapalli-Catana-2005              | √          |               |        | $d_e$        |                  |
| Chin-2010 ($P_{200} < 30\%$)       | √          |               |        |              | $D_{50}$         |
| Chin-2010 ($P_{200} > 30\%$)       | √          |               |        |              |                  |
Figure 6 | Measured and predicted SWCCs for sample C-1 with a dry density of 2.0 g/cm³ (a), sample C-2 with a dry density of 1.7 g/cm³ (b), sample C-2 with a dry density of 2.0 g/cm³ (c), sample C-3 with a dry density of 1.8 g/cm³ (d) and sample C-3 with a dry density of 2.0 g/cm³ (e).
Discussion of the limitations of the prediction models

Limitations caused by statistical samples

The prediction model uses statistics-based empirical equations and parameters, which are derived from the statistical samples selected when the model was established. If the statistical sample is significantly different from the sample to be tested, the use of the prediction model has certain limitations. The Chin-2010 model used 61 samples during the construction and inspection of the model.
There is only one sample similar to C-2 in physical properties. The Aubertin-2003 model used 36 samples when the model was constructed. Only the samples from Rassam & Williams (1999) are similar to the C-2 in this paper. As shown in Table 9, the porosity of this sample is 0.637, $D_{10}$ is 0.06 mm and $D_{60}$ is 0.3 mm. It can be seen that the statistical samples applicable to the above two models are quite different from the samples tested here. The $D_{10}$ of 15 samples used for the Aubertin-1998 model is lower by one order of magnitude than the samples in this paper. In theory, the finer the sample particles, the pore size is smaller in the sample, which may be the reason the existing prediction models generally estimate the low air-entry values.

A comparison between the experimental value from Rassam & Williams (1999) and the predicted value from Aubertin et al. (2003) shows that the predicted air-entry value is close in the two studies, but the predicted slope of the curve in the descending section is greater than that of the measured curve, as shown in Figure 8. In short, if the information on the particle size distribution of a given sample is limited, the prediction models cannot perform well in predicting the SWCCs for similar types of samples.

**Limitations on assumed particle shape and mineral compositions**

Some empirical coefficients in the models imply some assumptions for the sample particle shape and minerals. For example, Equation (12) in the Aubertin-2003 model related to the air-entry value in the model is a simplified form. The expression before the simplification is shown in the following equation (Aubertin et al. 2003):

$$h_{co} = \frac{\sigma \cos \beta_w \alpha}{\gamma_w} \frac{\alpha}{eD_H}$$

where $\sigma$ is the surface tension of water, $\beta_w$ is the contact angle, $\gamma_w$ is the weight of water, $\alpha$ is the shape factor of the particles and $D_H$ is the equivalent particle size that keeps the pore surface area of the sample unchanged. When simplified, $\alpha$ takes 10 and $\beta_w$ takes 0 degree, which assumes that the particles are all quartz. However, the

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**Table 9  | Physical parameters of tailing samples from the literature**

| Void ratio | $D_{10}$ (mm) | $D_{50}$ (mm) | $D_{60}$ (mm) | References |
|------------|---------------|---------------|---------------|------------|
| 0.57       | 0.0427        | 0.2259        | 0.2714        | Liang et al. (2003) |
| 0.637      | 0.06          | —             | 0.3           | Johari et al. (2006) and Saxton & Rawls (2006) |

Note: These parameters are similar to those of the sample C-2 with a dry density of 1.7 g/cm$^3$.
tailings are the product of manual crushing rather than natural weathering, so the tailing particles are very rough (Maqsoud et al. 2017). In addition, the shape factor may be different from the empirical value. The XRD analysis of the samples in this paper shows that the quartz content is only one-third, as shown in Table 10. Hence, the contact angle is not zero.

Taking C-2 with a dry density of $1.7 \times 10^3$ kg/m$^3$ as an example, by keeping the contact angle unchanged and changing the shape factor, the prediction results of the Aubertin-2003 model are obtained and shown in Figure 9. When the shape factor is close to 15, the air-entry value is closer to the measured value. If the increase in contact angle is considered, the shape factor should continue to increase.

Therefore, particle shape and mineral compositions are two important reasons to cause the deviation of the predicted value from the measured value.

Limitations caused by sample description indicators

Figure 10 shows the prediction results of the Aubertin-2003 model for samples C-2 and C-3 with different dry densities. The prediction results fail to reflect the change of the SWCC caused by the difference in dry density, which does not agree with the measured SWCC data in Figure 4. The Aubertin-1998 model also has the same issue. Both the two models lack suitable indicators to reflect the change of the dry density in tailings, which represents a change of the pore structure. Therefore, there is a large deviation between the prediction results and the measured data for Aubertin-1998 and Aubertin-2003 models. Models that are based on the single-point measurement method like the Vanapalli-Catana-2005 model can overcome this problem.

Discussion on the suitability of the prediction models

To further verify the suitability of the prediction models, the predicted models are used to predict the measured data in Wen et al. (2020), as shown in Figure 11. Figure 11 shows

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Table 10 | Mineral compositions of the three coarse-grained samples

| Mineral component | W-1  | W-2  | W-3  |
|-------------------|------|------|------|
| Quartz            | 26.65| 33.68| 39.92|
| Magnesiohornblende| 51.21| 43.39| 47.56|
| Oligoclase        | 7.05 | 6.92 | 2.18 |
| Chlorite          | 6.62 | 5.58 | 3.31 |
| Illite            | 7.22 | 8.7  | 4.98 |
| Litharge          | 1.25 | 1.74 | 2.05 |
that (1) for the tailing medium sand and tailing fine sand, the predictions from Aubertin-1998 and Aubertin-2003 models significantly deviate from the measured data (Figure 11(b) and 11(c)). Hence, the two models cannot be chosen as the prediction model. (2) For tailing silty sand, the prediction results from the Aubertin-2003 model are consistent with the measured data when the matric suction is less than 40 kPa. If the suction force is greater than 40 kPa, only the prediction of the Vanapalli-Catana-2005 model is close to the test data, as shown in Figure 11(d). (3) For the tailing medium sand, the prediction from the Chin-2010 model is better than the prediction from the Vanapalli-Catana-2005 model.

Based on the analysis of the prediction results, there are some limitations on the existing prediction models to describe soil-water characteristics of the tailings and dumping materials. (1) The biggest limitation comes from the deviation of sample physical properties from the assumed properties in the model. If the physical properties of a sample to be tested are significantly different from those in the model, the empirical equation used in the model will not be applicable to the sample. Therefore, in order to select an appropriate prediction model, more attention needs to be paid to the comparability of the physical property index between the real sample and the prediction model. (2) The prediction model has some assumptions about the particle and mineral composition of the sample. For special samples with unusually rough or smooth particles or containing large amounts of hydrophilic minerals or non-hydrophilic clay minerals, the relevant empirical values used in the models should be treated with caution. (3) At present, the prediction model established completely based on the particle size distribution curve still cannot consider the impact of pore structure changes on the SWCC well. For the SWCC of the sample under the change of porosity under consolidation, only the one-point method can be used for SWCC prediction.

In general, for cross-scale mine waste, tailing mud, tailing sand and dumping materials, the Vanapalli-Catana-2005 model can offer the best prediction of the SWCCs, given a suitable dataset to calibrate the model parameters.

**SWCC MODEL FOR THE EMERGENCY RISK ASSESSMENT OF MINE WASTES**

Tailing dams and dumps come with a potential risk of collapse in mines. Different from hydraulic earth-rock dams and slope engineering with relatively fixed structural
configuration, tailing dams or dumps formed by mine wastes always experience dynamic changes which can last until the mines are closed. This dynamic change not only requires the continuous update of the model of stability evaluation but also makes the consolidation state of the tailings evolved with time under the changing stress paths. Hence, it is necessary to evaluate the seepage stability of the tailing dam or dump in time. In particular, due to the unpredictable environmental conditions, the actual structure and operating conditions of tailing dams or waste dumps are always different from design regulations during the construction process. For example, the tailing site usually has slope escape and abnormal deformation. Also, the required SWCC data of the mine wastes cannot be completely measured under emergency conditions like rainstorm or flooding. Therefore, it is particularly urgent and important to make a preliminary judgment on the range of the SWCC parameters based on a small set of measured data. This is vital for emergency decision-makers to make a swift decision to avoid catastrophic risks under rainstorm or flooding conditions.

**Suggestion of an emergency SWCC model**

A framework to establish an appropriate SWCC model is given based on the stacking process in this section. Based on the statistics of tailing data from the literature and measured in this paper, the range and recommended values for the SWCC parameters are classified. The recommended parameters and the measured data are used in
an example simulation. The differences between the phreatic line and pore water pressure in the seepage processes are compared and discussed.

Generalization of the model

Without loss of generality, there are basically two main types of damming technology. One is to use a cyclone to build the dam, and the other is to select layered and compacted coarse tailings in front of the dam. Under the centrifugal force and vacuum of the cyclone, the coarse-grained tailings in the tailing slurry are separated from the fine-grained tailings and water. The coarse-grained tailings are used to build the sub-dam, and the mixture of fine-grained tailings and water is transported to the sedimentary shoal. Scatter-pipe alternating expulsion and the tailings flow separation also form the coarse-grained deposition area in front of the dam. Therefore, the SWCC model can be determined according to the particle size of the sedimentary tailings.

In the horizontal direction, two large areas are set, namely (1) dam body (coarse-grained tailings) and (2) deposited fine-grained tailings. From the crest of the dam, sandy, silty and clayey tailings may be distributed in sequence. According to the particle size, it is further divided into different areas: tailing gravel sand (2 mm); tailing coarse sand (0.5–2 mm); tailing medium sand (0.25–0.5 mm); tailing fine sand (0.074–0.25 mm); tailing silty sand (<0.074 mm); tailing silt; tailing silty clay and tailing clay. In the vertical direction, based on self-weight stress and consolidation age, the different dry densities are set based on the stratification.

For the dumping site, Wang et al. (201b) found that gravity separation results in inclined stratification characteristics and the reverse sequence layers with the upper coarse-grained particles and the lower fine-grained particles. Under this situation, the hydraulic properties on the down and vertical slope directions show strong anisotropy.

Divisional assignment of SWCC parameters

The SWCC model for emergency risk assessment adopts a divisional assignment method. Steps of this method are as follows: (1) the tailings are divided into coarse-grained tailings and fine-grained tailings. Combined with the SWCC data available in the literature, the recommended upper envelope, lower envelope and medium line for the FX fitting model are given based on the basic parameters obtained in this study. (2) The suggested average SWCC parameter values for coarse- and fine-grained tailings are given. Based on the recommended values from the China standard (Code for design of tailings facilities, GB 50865-2013) and this test, the SWCC parameters of the tailings can be selected according to Table 11. The measured data and the SWCCs with given SWCC parameters in Table 11 are shown in Figure 12. It can be seen that the prediction curves of the FX model have the hydraulic characteristics of the main materials of the tailing dam.

Influence on seepage characteristics

To further verify the validity of the recommended parameters in the emergency model in Table 11, a simulation

| Table 11 | Recommended model parameters for the emergency risk assessment model |
|----------|--------------------------------------------------------------------|
| **Index** | **TCS** | **TFS** | **TSS** | **TS** | **TSC** | **TC** |
| Characteristic indexes | | | | | | |
| $d_p$ (mm) | 0.35 | 0.2 | 0.074 | 0.05 | 0.035 | <0.02 |
| $d_{10}$ (mm) | 0.10 | 0.07 | 0.02 | 0.01 | 0.003 | 0.002 |
| $C_u$ | 3 | 3 | 4 | 6 | 10 | 5 |
| $\gamma$ (g/cm$^3$) | 1.8 | 1.85 | 1.9 | 2.0 | 1.95 | 1.8 |
| $e$ | 0.8 | 0.9 | 0.9 | 0.95 | 1.0 | 1.4 |
| Permeability coefficient | | | | | | |
| $k$ (cm/s) | $1.5 \times 10^{-3}$ | $1.3 \times 10^{-3}$ | $3.75 \times 10^{-4}$ | $1.25 \times 10^{-4}$ | $3.0 \times 10^{-6}$ | $2.0 \times 10^{-7}$ |
| SWCC–FX model Parameters | | | | | | |
| $a$ | 28.795 | 13.855 | 6.312 |
| $m$ | 2.052 | 1.645 | 1.341 |
| $n$ | 1.164 | 1.695 | 2.045 |

$d_p$, average particle size; $d_{10}$, effective particle size; $C_u$, uniformity coefficient; $\gamma$, natural unit weight; TCS, tailing coarse sand; TFS, tailing fine sand; TSS, tailing silty sand; TS, tailing silt; TSC, tailing silty clay; TC, tailing clay.
of unsaturated seepage processes in a tailing dam was done in this section. A sensitivity analysis of the SWCC parameters on the phreatic line and water head in the tailing dam was carried out. This simulation was focused on the change of dry shoal length caused by the fluctuation of the reservoir water level. The distributions and differences of the phreatic lines are given in Figure 13. The simulated water-level distributions at different monitoring points are shown in Table 12. It is clear that the recommended soil-water retention characteristics model and the related parameters can be used to predict water levels in tailing dams and waste dumps, which is very helpful for emergency risk assessment under rainstorm or flooding conditions.

**SUMMARY AND CONCLUSIONS**

In this study, representative coarse- and fine-grained tailings from a metallurgical mine were used to experimentally determine the soil-water retention characteristics of the
tailings. Three fitting SWCC models were used to explore the effects of particle size and compactness on the soil-water retention behavior. The suitability of the SWCC prediction models is compared and discussed in detail. Given the need of rapidly determining the SWCC parameters for emergency risk assessment under rainstorm or flooding conditions, the possibility of replacing the measured SWCCs with the predicted SWCC model is explored. The main conclusions are as follows:

1. The measured SWCC of coarse- and fine-grained tailings and waste dumps can be fit well using Gardner’s, VG’s and FX-SWCC’s models, respectively.

2. For the cross-particle scale mine waste, tailing mud, tailing sand and dumping materials, the Vanapalli-Catana-2005 model can achieve an acceptable accuracy for the prediction of SWCC parameters. By comparing the results from different prediction models, the applicability of the SWCC model is substantially affected by sample statistics used in model development. The assumptions of particle shape and mineral compositions in the model have a great influence on the calculation of the air-entry value. The effect of pore structure changes on the SWCC cannot be included in the existing models due to a lack of physical parameters to reflect the pore structure.

3. The effect of the threshold particle size ($d_{\text{thres}}$) that distinguishes coarse- and fine-grained tailings on waste dump SWCC predictions should be considered. For example, if fine-grained tailings are dominant, only the physical property indicators ($C_u$, $e$ and $d_e$) of fine particles ($d$ smaller than $d_{\text{thres}}$) are needed for the prediction model. That is to say, the influence of the relative abundance of the two-particle groups on the overall hydraulic properties needs to be considered.

4. Emergency decision-making to avoid catastrophic risks of tailing dam or waste dump collapse under rainstorm or flooding conditions requires an emergency SWCC model to calculate key risk indicators such as the infiltration line and pressure head. This study proposes a generalized emergency SWCC model for tailing dams and waste dumps under rainstorm or flooding conditions.

| Monitoring point ID | Monitoring section line ID | Normal water level | Flood level |
|---------------------|----------------------------|--------------------|-------------|
|                     |                            | $J_1$ | $J_2$ | $J_3$ | $J_1$ | $J_2$ | $J_3$ |
| A                   | C-1, $\rho_d = 2.0$      | 0.00  | 0.00  | 30.00 | 11.80 | 189.66 | 5.40  |
|                     | C-2, $\rho_d = 1.7$      | -289.62 | -119.09 | -372.01 | -165.72 | 121.72 | -18.64 |
|                     | C-2, $\rho_d = 2.0$      | -281.20 | -120.86 | -370.98 | -159.72 | 121.97 | -24.57 |
|                     | C-3, $\rho_d = 1.8$      | -278.92 | -112.62 | -362.75 | -157.77 | 122.42 | -21.93 |
|                     | C-3, $\rho_d = 2.0$      | -282.76 | -115.85 | -371.02 | -155.17 | 123.52 | -21.45 |
| B                   | C-1, $\rho_d = 2.0$      | 300.00 | 300.00 | 0.00  | 332.19 | 485.20 | 284.35 |
|                     | C-2, $\rho_d = 1.7$      | 25.96  | 177.24 | -72.42 | 112.79 | 413.00 | 263.79 |
|                     | C-2, $\rho_d = 2.0$      | 29.91  | 176.18 | -72.53 | 113.11 | 414.38 | 262.48 |
|                     | C-3, $\rho_d = 1.8$      | 30.69  | 184.37 | -65.66 | 113.12 | 414.73 | 263.97 |
|                     | C-3, $\rho_d = 2.0$      | 31.03  | 181.22 | -72.40 | 114.96 | 415.66 | 264.49 |
| C                   | C-1, $\rho_d = 2.0$      | 600.00 | 600.00 | 300.00 | 656.19 | 782.48 | 577.10 |
|                     | C-2, $\rho_d = 1.7$      | 353.21 | 474.57 | 196.29 | 414.37 | 709.88 | 553.17 |
|                     | C-2, $\rho_d = 2.0$      | 353.18 | 474.75 | 225.46 | 412.76 | 710.42 | 553.38 |
|                     | C-3, $\rho_d = 1.8$      | 357.16 | 484.38 | 232.31 | 407.95 | 709.48 | 552.84 |
|                     | C-3, $\rho_d = 2.0$      | 357.09 | 478.29 | 225.75 | 412.45 | 711.16 | 553.28 |

$\rho_d$, dry density ($10^3$ kg/m$^3$).
and a framework is developed to quickly determine SWCC parameters. The emergency SWCC model is based on statistical analysis, literature search and experimental results obtained by this study. A numerical simulation example shows that the emergency SWCC model is able to predict phreatic lines and water heads at different locations of a tailing dam, demonstrating that the model can provide good guidance for the emergency water retention assessment of tailing dams and waste dumps under rainstorm or flooding conditions.

**FUNDING**

This research is supported by the National Natural Science Foundation of China (grant nos 51674238, 41902258 and U1967208) and the National Key R&D Program of China (grant no. 2019YFE0100100-04).

**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

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First received 28 August 2020; accepted in revised form 26 February 2021. Available online 17 March 2021