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NOTE

Empirical equation for evaluating the dispersivity of cohesive soil

Henghui Fan and Lingwei Kong

Abstract: As indicated by the theory of a clay–water–electrolyte system, the dispersive mechanism of cohesive soil involves three aspects: low clay content, high sodium ion percentage, and strongly alkaline pH. Accordingly, an empirical equation was established with an associated procedure and criteria proposed for evaluating the dispersivity of cohesive soil. The equation consists of four soil physical and chemical indicators: liquid limit (W_L), clay content (P_C), sodium percentage in the pore water (P_S), and pH. The equation is $F = 4 - 0.01(2W_L + P_C - P_S) + 0.1\,\mathrm{pH}$, where F is the soil dispersivity value. Compared with the evaluation based on laboratory tests, the empirical equation had higher accuracy for the evaluation of the dispersivity of cohesive soil, and was thus conducive to greater engineering safety. This indicates that the proposed empirical equation is applicable for evaluating the dispersivity of cohesive soil in general engineering.

Key words: dispersive soil, dispersive mechanism, experimental evaluation, empirical equation.

Résumé : Tel qu'indiqué par la théorie du système argile-eau-électrolyte, le mécanisme de dispersion d'un sol cohésif implique trois aspects; un faible contenu en argile, un pourcentage élevé d'ions de sodium, et un fort pH alcalin. Ainsi, une équation empirique a été établie, avec une procédure associée et des critères proposés, pour l'évaluation de la dispersivité d'un sol cohésif. L'équation comprend quatre indicateurs physiques et chimiques du sol; soit la limite liquide (W_L), le contenu en argile (P_C), le pourcentage de sodium dans l'eau interstitielle (P_S), et le pH. L'équation est $F = 4 - 0{,}01(2W_L + P_C - P_S) + 0{,}1\,\mathrm{pH}$, où F est la valeur de dispersivité du sol. Lorsque comparée à l'évaluation basée sur des essais en laboratoire, l'équation empirique a une meilleure exactitude pour l'évaluation de la dispersivité des sols cohésifs et entraîne donc une sécurité d'ingénierie plus élevée. Ceci indique que l'équation empirique proposée est applicable pour l'évaluation de la dispersivité de sols cohésifs dans l'ingénierie générale. [Traduit par la Rédaction]

Mots-clés : sol dispersif, mécanisme de dispersion, évaluation expérimentale, équation empirique.

Introduction

Dispersive soil is a problematic soil type that has caused increasing concern in geotechnical engineering in recent years (Sherard et al. 1977; Hong and Sheng 1984; Lashkaripour et al. 2007). In low salinity water or purified water, the cohesion among fine particles of dispersive soil is largely or completely lost, and the granules that exist as aggregates are self-dispersed as clay particles to the original level (McElory 1987). The destruction of dispersive soil by water erosion is a complex physicochemical and mechanical process with fast and hidden characteristics that is potentially dangerous, and commonly causes the failure of embankments, such as the Wister dam in the USA (Petry 1974), the San Juan irrigation reservoir in Spain (Gutiérrez et al. 2003), and the Lingluo reservoir in China (Cui et al. 2004). Presently, the dispersivity of cohesive soil is determined through field investigation and laboratory tests. The field investigation mainly involves a site survey of abnormal erosion such as gullies and holes near the soil borrow area, whereas laboratory tests generally require soil analyses through the double hydrometer test, crumb test, pinhole test, soluble cations in pore water test, and exchangeable sodium percent test. Thus, the evaluation of the dispersivity of cohesive soil is relatively complex. The complexity of dispersive soil and the limitation of relevant knowledge have meant there are no algorithms for evaluating the dispersivity of cohesive soil to date. Despite the use of sodium percentage (P_S), exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR) in engineering practices, these single tests need to be combined with additional tests for accurate evaluation. Developing an algorithm has been an important research topic in geotechnical engineering. Evaluating the dispersivity of cohesive soil with algorithms can not only provide practical engineering algorithms, reduce work intensity, and improve work efficiency, but can also reveal the dispersive mechanism of the soil. Therefore, it is of great significance to understand the dispersivity of the soil.

Based on research of the dispersive mechanism of cohesive soil, this study addressed the physical and chemical influencing factors, established an empirical equation, and proposed the procedure and criteria for evaluating the dispersivity of cohesive soil. The proposed equation was verified by comparing obtained results with published experimental evaluation results. This work attempted to provide an algorithm with clear physical meaning, a simple calculation process, and reliable evaluation results for the identification of dispersive soil.

Dispersive mechanism of cohesive soil

The dispersive mechanism of cohesive soil is complex. Scientists usually utilize the mineral theory, cation theory, acidity (pH value) theory, or comprehensive theory (Holmgren and Flanagan 1977; Wang 1994; Wei et al. 2007) to explain the reasons for dispersivity. As indicated by the mineral theory, soil dispersivity is caused by sodium montmorillonite; in the cation theory, a large number of sodium ions in the soil thickens the electric double layer of soil particles, leading to the dispersivity of the soil; the acidity theory addresses soil dispersivity through the influence of pH on soil surface charge. All these have a certain theoretical

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basis, but each of them can be considered incomplete theories. Laboratory tests also indicate that a single theory is often unable to explain the reason of dispersivity for some soil types. Based on the theory of a clay–water–electrolyte system, Fan et al. (2010, 2012) studied the dispersive mechanism of cohesive soil and considered that the following three aspects: low clay content, high sodium ion percentage, and strongly alkaline pH, together with water as the external factor, impose influences on the repulsion and gravitation among soil particles, further affecting associated particle dispersivity and cohesion.

Soil clay

The particle size distribution of cohesive soil is generally dominated by silt and clay. Clay plays a decisive role in the engineering properties of soil. According to the engineering classification for soils, clay is generally defined as mineral grains with a diameter of <0.005 mm. Based on mineral composition, clay can be divided into three types: montmorillonite, illite, and kaolinite. Of these, montmorillonite is highly hydrophilic, followed by illite and kaolinite. Clay particles are very fine with large surface areas and strong adhesion, closely related to many properties of soil such as dispersivity, expansion, water absorption, and permeability. The main characteristic of cohesive soil is related to the great cohesion, which allows the existence of fine particles in aggregates. It is the stability of these aggregates in water that largely determines the engineering properties of the soil.

Regarding soil physical parameters, the Atterberg limits of cohesive soil can reflect the comprehensive influence of soil mineralogical composition and particle size. For example, along with the increases in clay and montmorillonite contents, the liquid limit increases accordingly.

Sodium ions

Sodium ions can exist in both solid and liquid forms in soil, and often transform between each other. Sodium ions that dissolve in pore water solution can exchange with other cations adsorbed on particle surfaces in a dynamic equilibrium state. As indicated by the theory of the diffuse double layer, the monovalent sodium ions increase the thickness of the diffuse double layer of soil particles, resulting in stronger repulsion than gravitation and a net potential energy performance of repulsion, which leads to soil dispersivity. In contrast, the divalent calcium and magnesium ions suppress the surface diffuse double layer of soil particles, resulting in decreased repulsion and increased gravitation among soil particles, which promotes mutual cohesion and strengthens the structural connection, resulting in low soil dispersivity.

Common indicators of sodium ion concentration in soil include exchangeable sodium percentage (ESP), sodium percentage (P_S), and sodium adsorption ratio (SAR), which are correlated to one another. These chemical indicators are commonly used to assess soil sodicity. The ESP is calculated as follows:

$$(1) \qquad \mathrm{ESP} = \frac{C_{\mathrm{Na}}}{\mathrm{CEC}} \times 100$$

where CEC is the cation exchange capacity (cmol/kg) and C_{Na} is the exchangeable sodium cations in the adsorbed layer (cmol/kg).

The P_S and SAR values come from the soluble cations in pore water test. The P_S and SAR values are calculated as follows:

$$(2) \qquad P_S = \frac{C_{\mathrm{Na}}}{C_{\mathrm{Ca}} + C_{\mathrm{Mg}} + C_{\mathrm{Na}} + C_{\mathrm{K}}}$$

$$(3) \qquad \mathrm{SAR} = \frac{C_{\mathrm{Na}}}{\sqrt{(C_{\mathrm{Ca}} + C_{\mathrm{Mg}})/2}}$$

where C_{Ca}, C_{Mg}, C_{Na}, and C_{K} are the concentrations of calcium, magnesium, sodium, and potassium ions in pore water, respectively ($1/n$ mmol/L).

pH

The value of pH determines the charge characters on the surfaces of the soil particles, so it has a significant impact on the engineering properties of the soil. In alkaline soils, an extended diffuse double layer is easily formed on the surfaces of soil particles to maintain dispersivity. Consequently, this kind of soil has high dispersivity and plasticity, particularly with substantial features such as water swelling and dehydration shrinkage. In addition, it has low shear strength. As for acidic soils, such as the Quaternary red clay in South China, the hydrogen ion concentration is high in pore solution, and exchangeable cations are dominated by aluminum. As a result, the diffuse double layer is suppressed and conductive to particle aggregation. In addition, it can be positively charged at the sides and angular parts of soil particles, allowing soil particles to tightly bind to each other through electrostatic attraction between positively charged sides–angles and negatively charged surfaces of soil particles.

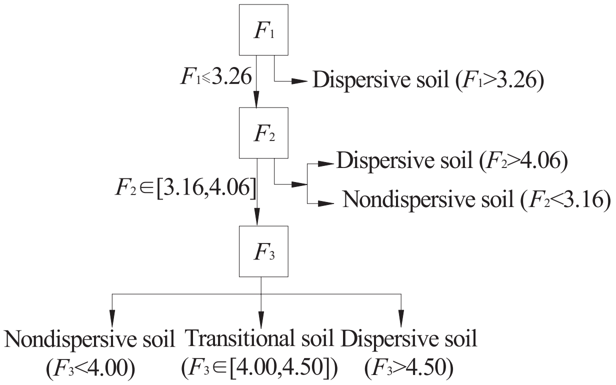
Empirical equation and evaluation criteria

Empirical equation

Fan et al. (2012) studied the relationship between the dispersivity of soil and the physical, chemical, and mineral properties of 48 soil samples. The indicators included the specific gravity, clay content, liquid limit, plastic limit, plasticity index, organic matter, pH, ESP, P_S, and the montorillonite content. The contents of these indicators were used as abscissa and the dispersivity from the identified tests as ordinate, and charts were made about the relationship between indicators and dispersivity. The following conclusions were drawn:

1. If the specific gravities of soil samples were <2.69, the soils might be nondispersive or transitional. If the specific gravities were >2.69, the dispersivity of soils was uncertain: that is, they might be dispersive, or transitional, or nondispersive.
2. If the clay contents of soil samples were <20%, the soils might be dispersive. If the clay contents were >20%, the soils might be nondispersive or transitional. In 48 soil samples only one was exceptional, which was dispersive even though the clay content was 21.5%.
3. If the liquid limits of soil samples were <30%, the soils might be dispersive or transitional. In 48 soil samples only two were exceptional, which were nondispersive although their liquid limits were 29.0% and 27.2%. If the liquid limits of soil samples were ≥30%, the soils might be nondispersive or transitional.
4. If the plastic limits of soil samples were <17%, the soils might be dispersive or transitional. In 48 soil samples only two were exceptional, which were nondispersive although their plastic limits were 15.0% and 15.2%. If the plastic limits of soil samples were ≥17%, the soils might be nondispersive or transitional.
5. If the plasticity indexes of soil samples were <15, the soils might be dispersive or transitional. In 48 soil samples only five were exceptional, which were nondispersive although their plasticity indexes were <15. If the plasticity indexes were ≥15, the soils might be nondispersive or transitional. In 48 soil samples only one was exceptional, which was nondispersive although its plasticity index was 16.6.
6. If the organic matters of soil samples were >5 g/kg, the soils might be nondispersive or transitional. If the organic matters were <5 g/kg, the dispersivity of soils was uncertain.
7. If the pH values of soil samples were <8.6, the soils might be nondispersive or transitional. If the pH values were ≥8.6, the

Fig. 1. Evaluation procedure and criteria for the dispersivity of cohesive soil.



soils might be dispersive or transitional. In 48 soil samples only one was exceptional, which was nondispersive although its pH value was 8.76.

8. If the ESP of soil samples were ≥9%, the soils might be dispersive or transitional. If the ESP were <9%, the dispersivity of soils was uncertain.
9. If the P_S of soil samples were ≥60%, the soils might be dispersive or transitional. In 48 soil samples only two were exceptional, which were nondispersive although their P_S were 61.3% and 76.0%. If the P_S were <60%, the dispersivity of soils was uncertain.
10. If the montmorillonite contents of soil samples were ≥4%, the soils might be dispersive or transitional. If the montmorillonite contents were <4%, the dispersivity of soils was uncertain.

From the above conclusions, the dispersivity of soil was influenced by physical and chemical factors. The physical factors were the clay content and the Atterberg limit. The chemical factors were the sodium ion concentration and pH value. Therefore, one should consider physical and chemical indicators of soil, including clay content, Atterberg limits, sodium ion concentration, and pH value when selecting parameters for the empirical equation. In this study, the liquid limit was considered as it can comprehensively reflect soil properties, so the empirical equation utilizes the liquid limit from the Atterberg limits. Based on the dispersive mechanism and mathematical analysis and experiences, the empirical equations were put forward as follows:

$$F_1 = 4 - 0.01(2W_L + P_C) \tag{4}$$

$$F_2 = 4 - 0.01(2W_L + P_C - P_S) \tag{5}$$

$$F_3 = 4 - 0.01(2W_L + P_C - P_S) + 0.1\text{pH} \tag{6}$$

where F_n is the soil dispersivity value, W_L is the liquid limit (%), P_C is the clay content (<0.005 mm) (%), P_S is the sodium percentage (soluble cations in pore water test), and pH is acidity.

The equation of F_1 is based on the physical factors. The W_L and P_C are the basic parameters easily obtained from the tests. The P_S and pH values, as the chemical factors, are added to the equations of F_2 and F_3 respectively, based on the equation of F_1.

Evaluation procedure and criteria

The evaluation procedure and criteria are shown in Fig. 1. If the F_1 value is satisfactory to identify the dispersivity of soil, it is unnecessary to calculate the F_2 or F_3 values. The dispersive reasons of this kind of soils are mainly physical properties, so these can be called the physical dispersivity. If the F_1 value is not satisfactory, it is necessary to calculate the equation of F_2, and so on, until F_3. If the F_2 or F_3 value is satisfactory to identify the dispersivity of soil, the dispersive reasons of this kind of soils are mainly chemical properties, so these can be called the chemical dispersivity. Certainly, if the four indicators can be obtained, all of the values of F_1, F_2, and F_3 can be calculated and used to identify the dispersivity of soil. The results of identification usually are the same.

Table 1 takes some soils as examples to explain how to use Fig. 1. The F_1 value of soil “I” is 3.314, which is >3.26, so it is dispersive. Because the F_1 values of the other five soil samples are <3.26, the F_2 values need to be calculated to identify the dispersivity of soils. The F_2 value of soil “II” is 3.060, which is <3.16, so it is nondispersive. The F_2 value of soil “III” is 4.119, which is >4.06, so it is dispersive. The F_2 values of the remaining three soils samples are between 3.16 and 4.06, so the F_3 values need to be calculated to identify the dispersivity. Because the F_3 value of soil “IV” is 3.968, which is <4.00, it is nondispersive. The F_3 value of soil “V” is 4.289 between 4.00 and 4.50, so it is transitional. The F_3 value of soil “VI” is 4.656, which is >4.50, so it is dispersive.

Data validation and analysis

Experimental data source

To ensure data integrity and reliability, experimental data were retrieved from literature and previously published research reports, including the Yinnen Project (Liu 1992; Wang et al. 1999), the Shangma Reservoir (Yue and Jin 1998), the Sanping and Xijiao Reservoir (Deng et al. 2000; Fan et al. 2005), the Banduo Hydropower Station (Fan et al. 2006; Li et al. 2006), the Xi'an Heihe Water Control Project (Fan et al. 2007), the Wenjiagou Hydropower Station (Fan et al. 2009), the Nanping Reservoir (Gao et al. 2009), the Ningmute Hydropower Station (Fan and Kong 2010), and the Dashixia Hydropower Station (Fan and Zhao 2012). A total of 110 sets of soil samples were used. It should be noted that the laboratory tests had at least three tests of the five tests: that is the double hydrometer test (D4221-11, ASTM 2011), pinhole test (D4647-06, ASTM 2006*a*), crumb test (D6572-06, ASTM 2006*b*), soluble cations in pore water test (Edgar 1991), and exchangeable sodium percent test (Sherard et al. 1972). These tests followed similar testing standards to the criteria for classification of dispersive potential.

Usually the double hydrometer test, pinhole test, crumb test, soluble cations in pore water test, and exchangeable sodium percent test have the same results, but sometimes not, so it is difficult to determine the dispersivity of soil with them. Because the pinhole test is a direct performance test, it is usually considered the most reliable. Fan et al. (2013) put forward the quantitative method to identify the results of those tests based on the characters of tests and experiences. Weight values were given to the double hydrometer test, crumb test, pinhole test, soluble cations in pore water test, and exchangeable sodium percent test, which were 20%, 20%, 40%, 10%, and 10% respectively, then the dispersive, transitional, and nondispersive values were calculated separately: (*i*) if the dispersive value was >50%, the soil was dispersive; (*ii*) if the dispersive value was 50% and the transitional value was ≥20%, the soil was dispersive; otherwise, it was transitional; (*iii*) if the dispersive value was <50% and the “dispersive and transitional” values were ≥50%, it was transitional. Otherwise, it was nondispersive. This method was so useful in identifying the dispersivity of soil that it could reduce the subjective mistake to some degree and make evaluation more complete, objective, and scientific.

Experimental data processing and discussion

The evaluation results of soil dispersivity were represented by letters: N for nondispersive soil, T for transitional soil, and D for dispersive soil. A diagram of the relationship between the soil sample F_n and soil dispersivity was drawn with the results of the laboratory test as the *y*-axis and that of soil sample F_n as the *x*-axis. Results are shown in Figs. 2–4 and Tables 2–3.

Table 1. Examples of how to use the F_n values and criteria.

No.	W_L (%)	P_C (%)	P_S (%)	pH	Result of F_1: F_1 value	Result of F_1: Result	Result of F_2: F_2 value	Result of F_2: Result	Result of F_3: F_3 value	Result of F_3: Result
I	25.3	18.0	60.9	8.51	3.314	Dispersive	—	—	—	—
II	38.0	27.0	9.0	8.19	2.970	—	3.060	Nondispersive	—	—
III	27.4	21.5	88.2	9.16	3.237	—	4.119	Dispersive	—	—
IV	29.0	18.0	1.8	7.10	3.240	—	3.258	—	3.968	Nondispersive
V	28.9	29.0	33.4	8.23	3.132	—	3.466	—	4.289	Transitional
VI	29.4	39.0	69.7	9.37	3.022	—	3.719	—	4.656	Dispersive

Fig. 2. Relationship between the F_1 value and soil dispersivity.

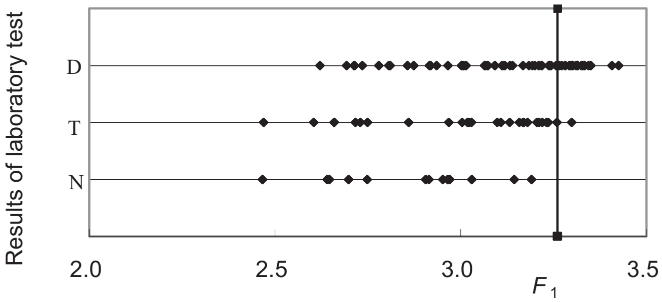


Fig. 3. Relationship between the F_2 value and soil dispersivity.

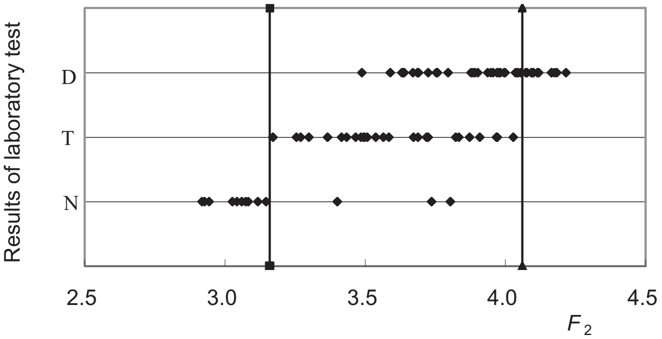
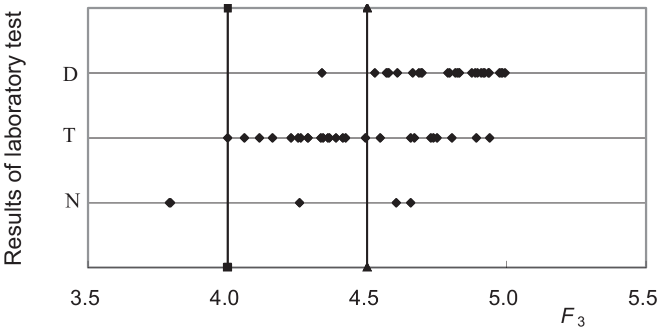


Fig. 4. Relationship between the F_3 value and soil dispersivity.



1. As shown in Figs. 2–4 and Table 2, the evaluation results of F_1 included 29 sets of soil samples with $F_1 > 3.26$, of which 28 sets were dispersive soils (96.6% accuracy), and one set was transitional soil (3.4% inaccuracy). According to F_2, 13 sets of soil samples with $F_2 > 4.06$ all belonged to dispersive soils (100% accuracy), whereas eight sets of soil samples with $F_2 < 3.16$ were all nondispersive soils (100% accuracy). According to F_3, there were 39 sets of soil samples with $F_3 > 4.50$, of which 28 sets were dispersive soils, nine sets were transitional soils, and two sets were nondispersive soils (71.8% accuracy and 28.2% inaccuracy); of the 19 sets of samples with $4.00 \leq F_3 \leq 4.50$, one set was dispersive soil, 17 sets were transitional soils, and one set was nondispersive soil (89.5% accuracy and 10.5% inaccuracy). Two sets of samples with $F_3 < 4.0$ were both nondispersive soils (100% accuracy).
2. As shown in Table 3, the accuracy of the 3-step evaluation based on F_n value was 87.3%. Of these, the identification of nondispersive soils based on F_n value evaluation and experimental evacuation had 100% accuracy. For the identification of transitional soil, the F_n value evaluation had 1.8% inaccuracy, with 0.9% of both nondispersive and dispersive soils misidentified. The identification of dispersive soils based on F_n value had 10.9% inaccuracy, with 1.8% nondispersive soils and 9.1% of transitional soils misidentified. Apparently, using F_n values to evaluate the dispersivity of cohesive soils yielded relatively high accuracy, and correspondingly, low inaccuracy, and the inaccuracy was mainly reflected in the identification of nondispersive soil as transitional or dispersive soil, or the identification of transitional soil as dispersive soil. This could be more secure to engineering projects.
3. In addition to the 110 sets of soil data for verification of the equation of $F_{1\to2\to3}$, another 81 sets of data were selected and processed. These experimental data were retrieved from the South Texas Project and Allen Creek (Marshall and Workman 1977), the Grenada Dam (Perry 1979), the Yinnei Engineering (Wu 1989), the Baise Reservoir (Fan and Gao 2005), the Kenzwat Reservoir (Gao and Fan 2005; Yu et al. 2011), the Guangxi Reservoir (Fan and Gao 2007), the Tingkou Reservoir (Fan and Gao 2010), the Songtashan Reservoir (Fan and Kong 2012). Of these, 30 sets of data that meet the requirements of the equation of F_1 and F_2 were analyzed and compared, whereas the evaluation of the remaining 51 sets required pH data for calculation of F_3 ($3.16 \leq F_2 \leq 4.06$).

Of the experimental data that satisfied the equation of F_1, three sets of soils were identified as dispersive soils based on the F_1 value. The same evaluation results were obtained via laboratory tests, thus yielding 100% accuracy. Of the experimental data that satisfied the equation of F_2, five sets of soil samples were identified as dispersive soils based on the F_2 value, and the same evaluation results were also obtained via laboratory tests, accounting for the 100% accuracy. There were 22 sets of soil samples classified as nondispersive soils based on the F_2 value, of which 20 sets were identified as nondispersive soils with 90.9% accuracy. The remaining two sets of samples included one set of transitional soil and one set of dispersive soil.

The results indicate that it is practical to use the F_n value for evaluation of the dispersivity of cohesive soil, as it features high accuracy and the evaluation results are conducive to the safety of engineering projects.

Conclusions

1. In engineering practice, soil chemical properties such as pH value and sodium ion percentage need to be determined in addition to basic soil physical parameters such as specific gravity, Atterberg limits, and mechanical composition. Experimental data should be accumulated to further examine the feasibility of the equation of F_n.

Table 2. Comparison of evaluation results based on laboratory tests and the dispersivity value F_n.

Experimental evaluation		F_n-based evaluation				
Soil type	Sample number (sets)	Soil type	F_1 (sets)	F_2 (sets)	F_3 (sets)	Sum (sets)
Nondispersive	13	Nondispersive	—	8	2	10
		Transitional	—	—	1	1
		Dispersive	—	—	2	2
Transitional	27	Nondispersive	—	—	—	0
		Transitional	—	—	17	17
		Dispersive	1	—	9	10
Dispersive	70	Nondispersive	—	—	—	0
		Transitional	—	—	1	1
		Dispersive	28	13	28	69

Table 3. Accuracy of the soil dispersivity evaluation based on the dispersivity value F_n.

			Inaccuracy and distribution (sets)				Inaccuracy and distribution (%)		
Soil type	Experimental evaluation (sets)	F_n-based evaluation and experimental evaluation yielding the same results (sets)	Nondispersive	Transitional	Dispersive	Accuracy (%)	Nondispersive	Transitional	Dispersive
Nondispersive	13	10	—	1	2	76.9	—	7.7	15.4
Transitional	27	17	0	—	10	63.0	0	—	37.0
Dispersive	70	69	0	1	—	98.6	0	1.4	—
Sum	110	96	0	2	12	87.3	0	1.8	10.9

2. The dispersivity of soil is very important to evaluate the seepage stability of hydraulic structures, and is directly related to the cost and safety of relevant buildings. Due to the complexity of soil, the evaluation of the dispersivity of soil for some important constructions should be carried out via laboratory tests as far as possible in combination of actual conditions. For general engineering projects, the empirical equation of F_n can be used for the evaluation of soil dispersivity.

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