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ORIGINAL PAPER

Dispersivity Identification and Modification with Lime of Soil in Huaaopao's Water Conservancy Project

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Abstract Water-retaining structures built with or on dispersive soil may easily be destroyed then after dangerous accidents associated with dispersive soil conditions, such as piping, caves and gullies, can occur. This study aims to propose a complete procedure to be followed when there is dispersive soil in water conservancy engineering or geotechnical engineering. The field investigations, empirical formulas and laboratory tests were conducted to define the dispersivity of Huaaopao soil samples. Among them, laboratory tests include pinhole tests, crumb tests, double hydrometer tests, pore water soluble cation tests and exchangeable sodium ion percentage tests. The dispersive mechanisms of the soil samples with dispersivity were analyzed from physical and chemical views. And the modified dose of lime on the dispersive soil samples was tested by pinhole tests and crumb tests. The results show that the soil samples TK4, TK8 to TK13 were dispersive, the soil sample TK15 was transitional, and the soil sample TK21 was not dispersive. The clay content of TK9 was less than 10% (physical level); the pH, the ESP and the PS were greater than 9.5, 7% and 60% (chemical level), respectively, resulting in its dispersivity. The TK4, TK8, TK10 to TK13 were dispersive only because of chemical factors with higher pH, ESP and PS. It is suggested to use 1 ~ 2% lime (mass fraction) to alter the dispersivity of dispersive soil samples in Huaaopao water conservancy project.

Keywords Problematic soil · Dispersive soil · Identification methods · Dispersive mechanism · Lime modification

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1 Introduction

The study of identification and modification of dispersive soil has always been one of the important and hot topics concerned by water hydraulic and geotechnical experts and scholars from all over the world (Wood et al. 1964; Sherard et al. 1972; Gerber and Harmse 1987; Watermeyer et al. 1991; Gutiérrez et al. 2003; Vinod et al. 2010; Umesh et al. 2011; Ouhadi et al. 2012; Marchuk et al., 2013; Nayak et al. 2014; Goodarzi and Salimi 2015; Maharaj et al. 2015; Premkumar et al. 2016; Rengasamy et al. 2016; Shoghi et al. 2017; Vakili et al. 2017, 2020; Abbasi et al. 2018; Han et al. 2018, 2022a, b; Moravej et al. 2018; Mohanty et al. 2019; Sadeghi et al. 2019; Sihag et al. 2019; Bershov et al. 2020; Fernando, 2010; Consoli et al. 2021; Filho et al. 2021; Liu et al. 2021; Türköz et al. 2021; Mallikarjun 2022). According to literature investigation, dispersive soil has been found in Australia, America, Brazil, Thailand, Greece, Canada, New Zealand, South Africa and China (Wood et al. 1964; Sherard et al. 1972; Bourdeaux and Imaizumi 1977; Cole et al. 1977; Coumoulos 1977; Dascal et al. 1977; Riley 1977; Qian 1981; Gerber and Harmse 1987; Bell and Maud 1994). Most earth dams, embankments and road foundations that were built with or on dispersive soil had occurred serious erosion problems, such as piping, caves and gullies, which brought huge economic losses and even threatened the safety of human life. And thus, it is important to identify and preprocess the dispersivity of engineering soil.

Some scholars tried to establish the relationship between dispersivity and basic geotechnical property indexes, so as to quickly identify the dispersivity of soil. Zhang (2010) established the three-layer BP neural network model with describing a relationship between five parameters of exchangeable sodium ion percentage, total exchangeable cations, pH, organic matter, clay content and dispersivity. Fan and Kong (2013) put forward a series of empirical formulas which only need liquid limit, clay content, sodium ion percentage and pH. Ju (2015) established and compared the traditional BP neural network of seven parameters and the PCA–BP neural network of four parameters and recommend the latter. Zhang et al. (2022) discussed the feasibility of using eleven parameters to identify the dispersivity of soil.

And the other scholars designed some special tests for identifying dispersive soil. Currently and commonly used are pinhole test (PT), crumb test (CT), double hydrometer test (DHT), pore water soluble cation test (PWSCT) and exchangeable sodium ion percentage test (ESPT). PT was proposed by Sherard et al (1976) to study erosion behavior of medium and small cracks or small holes in dams. CT was designed by simplifying the Emerson's soil aggregates classification method (Emerson 1967). DHT (previously often called dispersivity test) was first proposed by Volk (1938) to determine the dispersivity of soil by particle analysis. From the perspective of soil chemistry, PWSCT and ESPT were introduced from Agriculture Field (ref. Agriculture Handbook No. 60 1954). The former focused on the content of sodium cations in soil pore water at liquid limit, and the latter preferred that can be adsorbed by soil particles. With further development of dispersive soil research, researchers and engineers had noticed that the dispersivity discriminant results of the same soil samples under different discriminant tests are not always consistent with each other. Therefore, Fan et al. (2013) and Ju et al. (2016) offered different weight analysis methods, and Bell and Walker (2000) designed one score table. All in all, the identification of dispersive soil is complex, and this article attempts to propose a systematic discrimination procedure.

This article obtained the dispersivity properties of nine Huaaopao soil samples by field investigation, empirical model and laboratory tests, analyzed the dispersive mechanisms of some dispersive soil samples from physical and chemical views and advised the dose of modified material lime by PTs and CTs. The results could provide references for erosion disaster prevention in water conservancy engineering or geotechnical engineering.

2 Materials and Methods

2.1 Physicochemical and Mineral Properties of Soil Samples

Huaaopao water conservancy project is located in western Songyuan City, Jilin Province, China. The main task of this project is to safeguard Chunnabo relics groups from the Huaaopao water storage. The total length of the earth dam axis is 8 047 m, and the maximum earth dam height is 17.6 m. The studied soil was taken from dam foundation and two material fields.

The physicochemical properties (listed in Table 1) of Huaaopao soil samples were strictly tested according to the GB/T 50123-2019 and SL 237-1999 standards, Agriculture Handbook No.60 1954. The specific gravities (SG) of the studied soil samples were 2.67–2.70. The liquid limits (LL) were 27.5–44.2%, plastic limits (PL) were 15.5–19.0% and the plastic indexes (PI) were 10.2–27.2%. All soil samples were defined as low-liquid-limit clay soil according to a relationship between LL < 50% and PI > 0.73 (LL-20). The particle analysis results showed that the contents of sands (0.075–2 mm) were 2.4–36.4%, of clay (< 0.005 mm) and slit (0.005–0.075 mm) were 63.6–97.6%. The maximum dry densities (ρ_{dmax}) and optimum moisture contents (OMC) were 1.67–1.79 g/cm^3 and 12.5–17.3% separately according to compaction tests. The pH values, soluble salt content (SSC), proportion of sodium ions in pore water (PS) were

Table 1 Physical and chemical properties of Huaaopao soil samples

Soil samples	SG	LL/ %	PL/ %	PI/ %	Particle analysis/%			ρ_{dmax}/ (g·cm^{-3})	OMC/ %	pH	SSC/ (g·kg^{-1})	PS/ %
					Sand	Slit	Clay					
TK4	2.68	30.0	15.5	14.5	32.7	47.8	19.5	1.79	12.5	10.46	11.0	97.4
TK8	2.68	28.2	17.0	11.2	21.5	65.0	13.5	1.75	12.8	10.04	6.9	91.3
TK9	2.67	28.0	17.8	10.2	36.4	55.1	8.5	1.69	13.4	9.96	9.0	99.8
TK10	2.69	32.5	17.5	15.0	12.9	62.6	24.5	1.75	15.3	10.31	12.4	99.8
TK11	2.70	36.0	19.0	17.0	11.1	59.4	29.5	1.76	15.8	10.39	11.9	99.9
TK12	2.68	27.5	15.5	12.0	19.0	65.0	16.0	1.71	13.9	10.38	7.7	76.0
TK13	2.70	44.2	17.0	27.2	2.4	62.6	35.0	1.67	17.3	10.41	5.7	99.9
TK15	2.70	35.0	18.5	16.5	3.7	73.3	23.0	1.74	16.0	9.70	6.6	93.3
TK21	2.69	35.0	18.5	16.5	16.3	64.2	19.5	1.76	15.9	8.97	1.0	54.9

8.97–10.46, 1.0–12.4 g/kg and 54.9–99.9%, respectively, according to different chemical tests.

The mineral properties of Huaaopao soil samples are shown in Table 2. The non-clay minerals were quartz (Q), accounting for 50.9–89.3% of the total mineral amount, followed by K-feldspar (K-Fel) and plagioclase (Pla), accounting for 1.8–33.3%, and calcite (Cal), dolomite (Dol) and hornblende (Hor), accounting for 0–12.0%. The clay mineral components were illite (Ill), smectite (Sme), kaolinite (Kao) and chlorite (Chl), accounting for 1.7–5.7, 0.6–6.0, 0.4–1.5 and 0.5–1.8% separately.

2.2 Dispersivity Identification Methods

1. Erosion could be divided into internal erosion and external erosion according to different damage locations. Clay particles pass through internal cracks under the action of seepage water and severely lose, which lead to engineering disasters

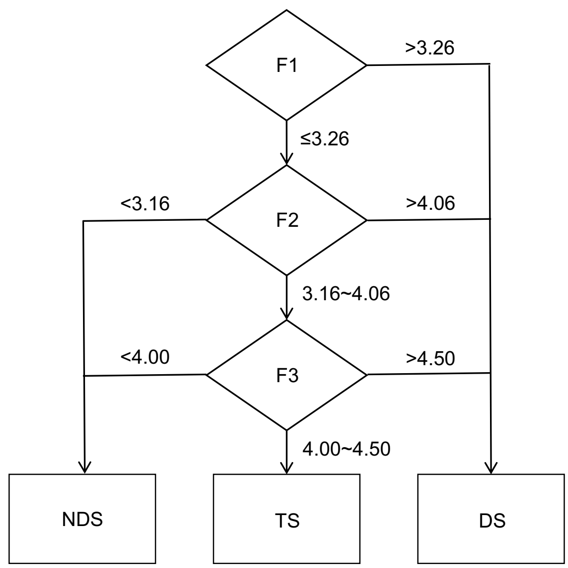

Fig. 1 Procedure and standard of the empirical model

Table 2 Mineral properties of Huaaopao soil samples

Soil samples	Non-clay mineral content/ %						Clay mineral content/ %			
	Q	K-Fel	Pla	Cal	Dol	Hor	Ill	Sme	Kao	Chl
TK4	65.9	3.4	7.5	2.5	7.7	0.0	4.6	6.0	1.0	1.3
TK8	58.2	6.6	17.4	2.1	0.0	9.2	2.7	2.6	0.5	0.7
TK9	89.3	1.8	5.4	0.0	0.0	0.0	1.7	0.6	0.6	0.7
TK10	50.9	33.3	7.8	0.0	0.0	0.5	3.5	1.3	1.2	1.5
TK11	56.9	5.5	15.5	3.7	0.0	3.6	5.7	5.8	1.5	1.8
TK12	71.9	12.3	6.6	1.3	3.0	1.0	1.7	1.3	0.4	0.5
TK13	62.3	11.8	15.1	2.8	0.0	0.0	3.1	3.4	0.6	1.0
TK15	52.1	14.1	9.2	12.0	0.0	0.0	5.0	5.3	1.0	1.3
TK21	60.8	6.9	10.0	8.9	0.0	1.8	4.5	5.3	0.8	1.0

such as piping (ref. Figs. 2 and 3 of Nwe and Kyaw 2018), channel (ref. Figs 1, 2 and 3 of Nwe and Kyaw 2018), tunnel (ref. Figure 1 of Hardie et al. 2007), cave (ref. Fig. 1 of Sadeghi et al. 2019), landslide and dam break (ref. Figs. 1 and 7 of Gutiérrez et al. 2003). It is called internal erosion. External erosion refers to the loss of clay particles through the surface of structures under the action of rainwater or surface water, and the commonly engineering disasters are rill and gully (ref. Figure 11 of Han et al. 2022a, b).

2. The advantage of suggested empirical model (Fan and Kong 2013) is that has higher accuracy and simple parameters with clear physical meanings. The procedure and standard are shown in Fig. 1. Among them, DS represents dispersive soil, TS represents transitional soil, NDS represents non-dispersive soil, and the calculation formulas of F1, F2 and F3 are as follows:

$$F1 = 4 - 0.01 \times (2 \times LL + Clay) \quad (1)$$

$$F2 = 4 - 0.01 \times (2 \times LL + Clay - PS) \quad (2)$$

$$F3 = 4 - 0.01 \times (2 \times LL + Clay - PS) + 0.1 \times pH \quad (3)$$

where Fn is dispersivity value of soil; the others are seen in Table 1.

1. The procedure and criteria of PT, CT and DHT were referenced ASTM D4647-13, ASTM D6572-13 and ASTM D4221-18, separately. The procedure of PWSCT and ESPT was referenced Agriculture Handbook No.60 (1954) and the criteria of that referenced Qian (1981). The identification criteria of five dispersivity identification tests are summarized in Table 3.It is suggested to use the weight analysis method (Fan et al. 2013) when the above five test results are not consistent. The weighted values of the PT, CT, DHT, PWSCT and ESPT are 40%, 20%, 20%, 10% and 10%, respectively. The weight values of non-dispersivity, transition and dispersivity are calculated to identify according to Fig. 2.

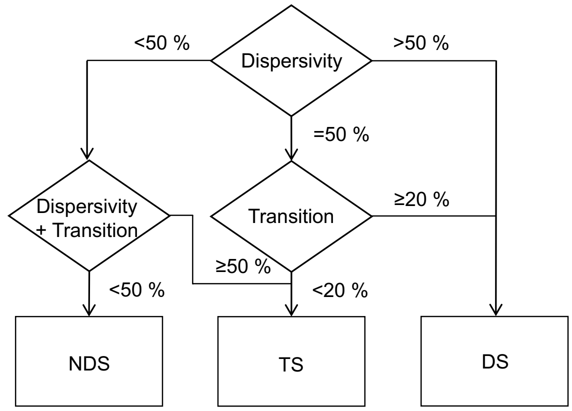

Fig. 2 Procedure and standard of the weight analysis method

3 Results and Discussions

3.1 Field Investigation

Huaaopao Lake area is a typical grassland landscape, and some field photographs are shown in Fig. 3. There is an obvious gully phenomenon on the soil

Table 3 Criteria of dispersivity identification tests

Tests	PT		CT		DHT	PWSCT	ESPT	Results
Parameters	Phenomenon	Grade	Phenomenon	Grade	DD	PS	ESP	
Criteria	A pinhole enlarges rapidly and the effluent is sufficiently turbid under 50 mm head	D1, D2	Moderate and strong reaction	3 and 4	> 50%	> 60%	> 15%	DS
	A pinhole enlarges slowly and the effluent is relatively turbid under 50 or 180 mm head	ND4, ND3	Slight reaction	2	30–50%	40–60%	7–10%	TS
	A pinhole does not change and the effluent is sufficiently clear under 380 or 1 020 mm head	ND2, ND1	No reaction	1	< 30%	< 40%	< 7%	NDS

DD, dispersivity degree; ESP, exchangeable sodium ion percentage

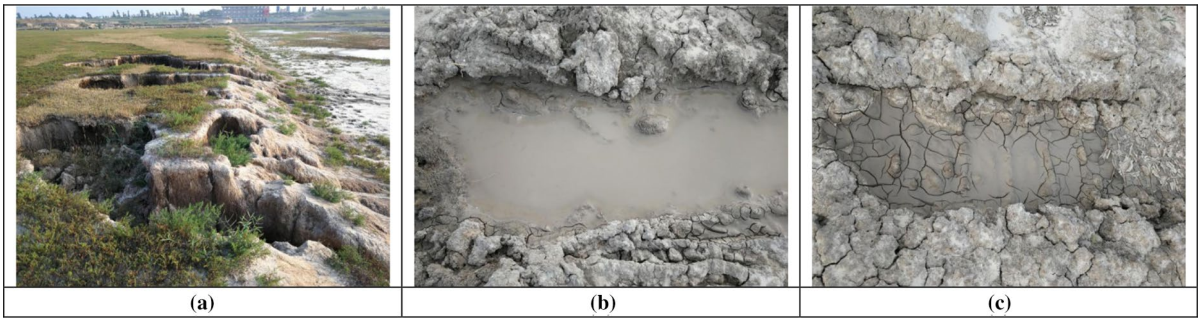

Fig. 3 Photographs of the Huaaopao soil in the field: **a** gully phenomenon, **b** dark water, **c** crack behavior

slope. The water in the puddles in the area was not clear soon. Cracks and salt crystal particles appeared on the soil surfaces after the water dried. In addition, plants with resistance to salt alkalescence, such as suaeda salsa, chloris virgata, calla lily, wormwood and foxtail grass, were widely distributed in this area. Therefore, the field investigations suggested that the Huaaopao soil displayed obvious field geological characteristics of dispersive soil.

3.2 Empirical Model

The results of the empirical model comprising identifications of the soil samples are listed in Table 4. The TK8, TK9 and TK12 samples were categorized as dispersive soil because their F1 values were above 3.26. The TK4 and TK10 samples were categorized as dispersive soil because their F2 values were above 4.06. The TK11, TK13, TK15 and TK21 samples were categorized as dispersive soil because their F3 values were above 4.50. And thus, all nine soil samples were estimated to be dispersive from the empirical model.

3.3 Laboratory Tests

The PT and CT results of Huaaopao soil samples are shown in Table 5, and the photographs of these tests results are shown in Figs. 4 and 5, respectively. The identification results of CTs were same as of PTs, that is, the TK4, TK8 to TK13 belonged to dispersive soil, the TK15 belonged to transitional soil, and the TK21 belonged to non-dispersive soil. According to the PT results, the TK4, TK8–TK13 soil samples were seriously eroded under the 50-mm head, and the cloudiness of the flow water of former six was dark and of latter one was moderately dark. The TK15 showed weak dispersivity behavior that cloudiness of the flow water was slightly dark and the hole size after test was 1.5 mm. The TK21 was not eroded under the 1020-mm. According to the dispersive phenomena in beakers, the TK4, TK8–TK13 were grade 4, the TK15 was grade 2, and the TK21 was grade 1.

The DHT, PWSCT and ESPT results of Huaaopao soil samples are shown in Table 6. The DD of the soil samples except TK15 was 7.7–28.6% (< 30%) and of TK15 was 30.4% (30–50%). And the TK4, TK8

Table 4 Identification results of the empirical model of the Huaaopao soil samples

Soil samples	F1	Results	F2	Results	F3	Results	Final results
TK4	3.205	–	4.204	DS	5.250	–	DS
TK8	3.301	DS	4.275	–	5.279	–	DS
TK9	3.355	DS	4.268	–	5.264	–	DS
TK10	3.105	–	4.103	DS	5.134	–	DS
TK11	2.985	–	3.983	–	5.022	DS	DS
TK12	3.290	DS	4.289	–	5.327	–	DS
TK13	2.766	–	3.526	–	4.567	DS	DS
TK15	3.070	–	4.003	–	4.973	DS	DS
TK21	3.105	–	3.654	–	4.551	DS	DS

Table 5 Identification results of the PTs and CTs of the Huaaopao soil samples

Soil samples	PT							CT	
	Head/ mm	Test time for given head/ min	Final flow rate/ ml·s^{-1}	Cloudiness of flow	Hole size after test/ mm	Grade	Results	Grade	Results
TK4	50	10	0.8	Dark	3–6	D1	DS	4	DS
TK8	50	10	0.9	Dark	3–12	D1	DS	4	DS
TK9	50	5	0.7	Dark	4–12	D1	DS	4	DS
TK10	50	10	0.7	Dark	2–3	D1	DS	4	DS
TK11	50	10	0.4	Dark	2	D1	DS	4	DS
TK12	50	5	0.9	Dark	2–6	D1	DS	4	DS
TK13	50	10	0.9	Moderately dark	2	D2	DS	4	DS
TK15	50	10	0.5	Slightly dark	1.5	ND4	TS	2	TS
TK21	1020	5	1.8	Clear	1	ND1	NDS	1	NDS

to TK13, and TK21 belonged to NDS and the TK15 belonged to TS from the DHT results. The PS values and ESP values of the soil samples except TK21 were 76.0–99.9 (> 60%) and 50–90.6 (> 7%), respectively, and of TK21 were 54.9% (40–60%) and 3.4% (< 7%), respectively. Hence, the TK4, TK8 to TK15 belonged to TS according to the ESPT and PWSCT results. The TK21 belonged to TS according to the PWSCT result and belonged to NDS according to the ESPT result.

It is obvious that the above five tests results are not perfectly consistent and the dispersivity identification of the Huaaopao soil samples were assessed by using a weight analysis method. The calculation results of weight analysis are listed in Table 7. It could be obtained that the weights of dispersivity of the TK4, TK8–TK13 were above 50%, and of the TK15 and TK21 were below 50%. The sum weights of dispersivity and transition of the TK15 were higher than 50% and of the TK21 was lower than 50%. Thus, the TK4, TK8–TK13 were dispersive, the TK15 was transitional and the TK21 was non-dispersive according to the weight analysis method.

3.4 Analysis of Dispersive Mechanism

When dispersive soil is immersed in low salt water or pure water, the apparent cohesion between clay particles disappears, and the aggregates disperse to the original clay particles (Zhang et al. 2015; Abbasi et al. 2018; Han et al. 2020). Many factors governing the susceptibility of soil aggregates to dispersivity can be attributed to the physical, chemical and mineral property indexes of the soil and to the ion concentrations of the environmental water. The consensus reached is that soil with high sodium concentrations and high pH values and water with low salt concentrations promote dispersivity (Jiang 1986; Chorom et al. 1994; Ouhadi and Goodarzi 2006; Fernado 2010; Fan and Kong 2013; Marchuk et al. 2013; Abbaslou et al 2016; Nwe and Kyaw 2018; Farahani et al. 2019; Zhang et al. 2022), and it could be explained by DLVO theory. The thickness of the double layer is directly proportional to the square root of the temperature and inversely proportional to the ion valence and the square root of the solution concentration, as shown in Eq. (4). The cations in soil generally include Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}. Under the same solution concentrations, temperatures and other parameters, the thickness of a double layer of Na^{+} is twice that of Ca^{2+}. Furthermore, the hydrate radius of sodium is larger than that of calcium in the solution of a soil–water-electrolyte system (Qiu 1984). When the surface charges of clay particles are constant, the repulsive potential energy is directly proportional to the thickness of the double layer. Thus, if there is a high sodium content in a given soil sample, the thickness of the double layer will be larger, the repulsion between the soil particles will be greater than the attraction between them, and the soil will have a dispersivity tendency. The pH value can have a great effect on the thickness of the double layer by changing the charges on the surfaces of the soil particles (Chorom et al. 1994). The stronger the alkalinity is, the more charges there are, and the more sodium ions

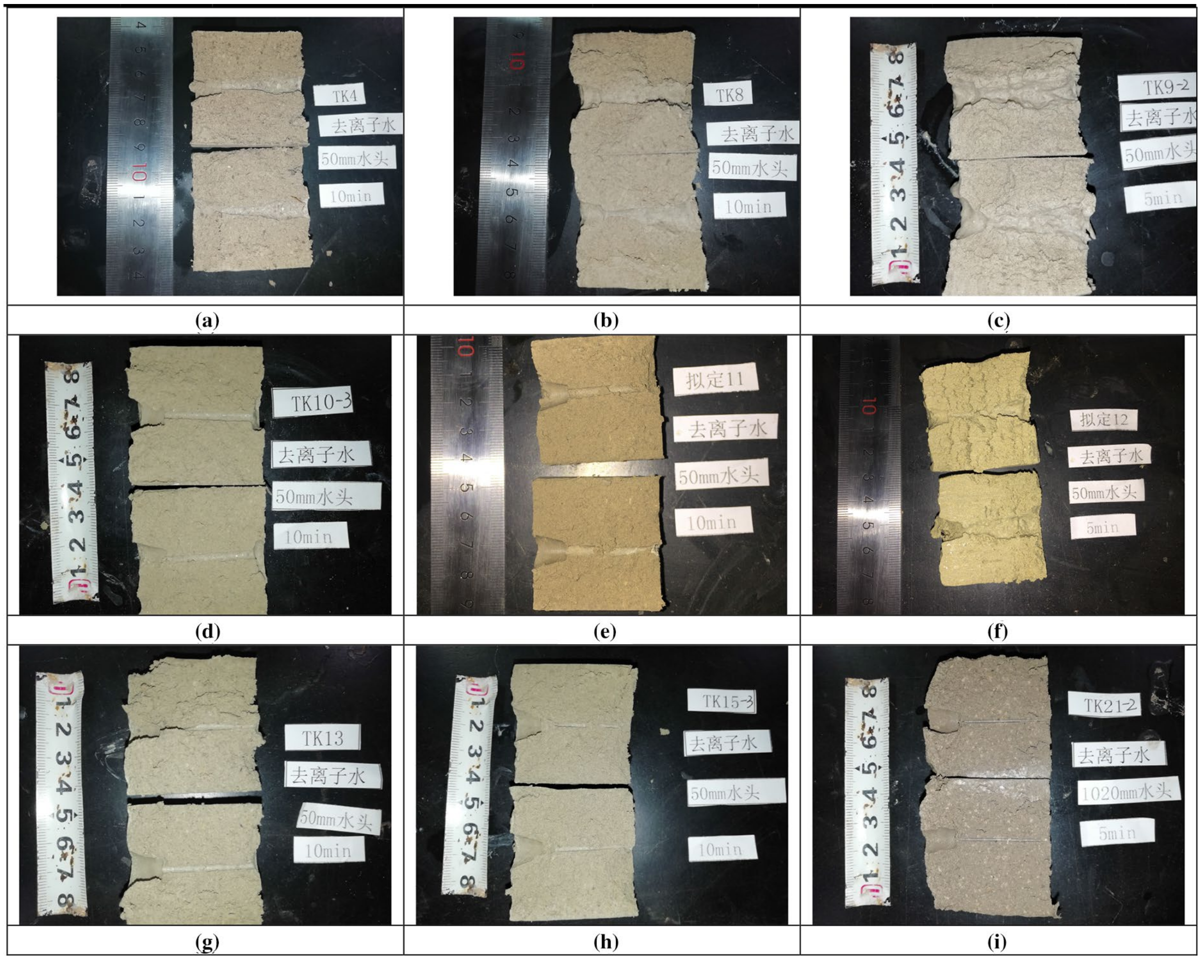

Fig. 4 Photographs of the Huaaopao soil samples after PT: **a** TK4, 50-mm head, 10-min duration, **b** TK8, 50-mm head, 10-min duration, **c** TK9, 50-mm head, 5-min duration, **d** TK10, 50-mm head, 10-min duration, **e** TK11, 50-mm head, 10-min duration, **f** TK12, 50-mm head, 5-min duration, **g** TK13, 50-mm head, 10-min duration, **h** TK15, 50-mm head, 10-min duration, **i** TK21, 1020-mm head, 5-min duration

are adsorbed, resulting in a thicker double layer and a larger repulsion; in this case, the particles easily disperse.

$$\frac{1}{\kappa} = \left(\frac{\varepsilon k_B T}{2e^2 Z^2 N_A n_0}\right)^{1/2} \quad (4)$$

where $1/\kappa$ is the dimension of the double electric layer thickness, e is the charge unit, Z is the ion valence, N_A is the Avogadro constant, n_0 is the electrolyte concentration in the solution, ε is the dielectric constant, k_B is the Boltzmann constant and T is the thermodynamic temperature.

It can be considered that ESP > 7% and PS > 60% can reflect the high proportion of sodium according to the criteria of ESPT and PWSCT and extremely strong alkalinity (pH > 9.5) can reflect the high pH according to general experience. However, it should be noted that meeting these conditions only shows that the studied soil sample has the potential of dispersivity. The soil sample may not belong to dispersive soil due to other reasons that promote flocculation such as a certain amount of clay particles or organic matters.

Clay particles are fine and have large surface areas; thus, enough clay particles provide better flocculation cohesion. On the contrary, less clay particles will

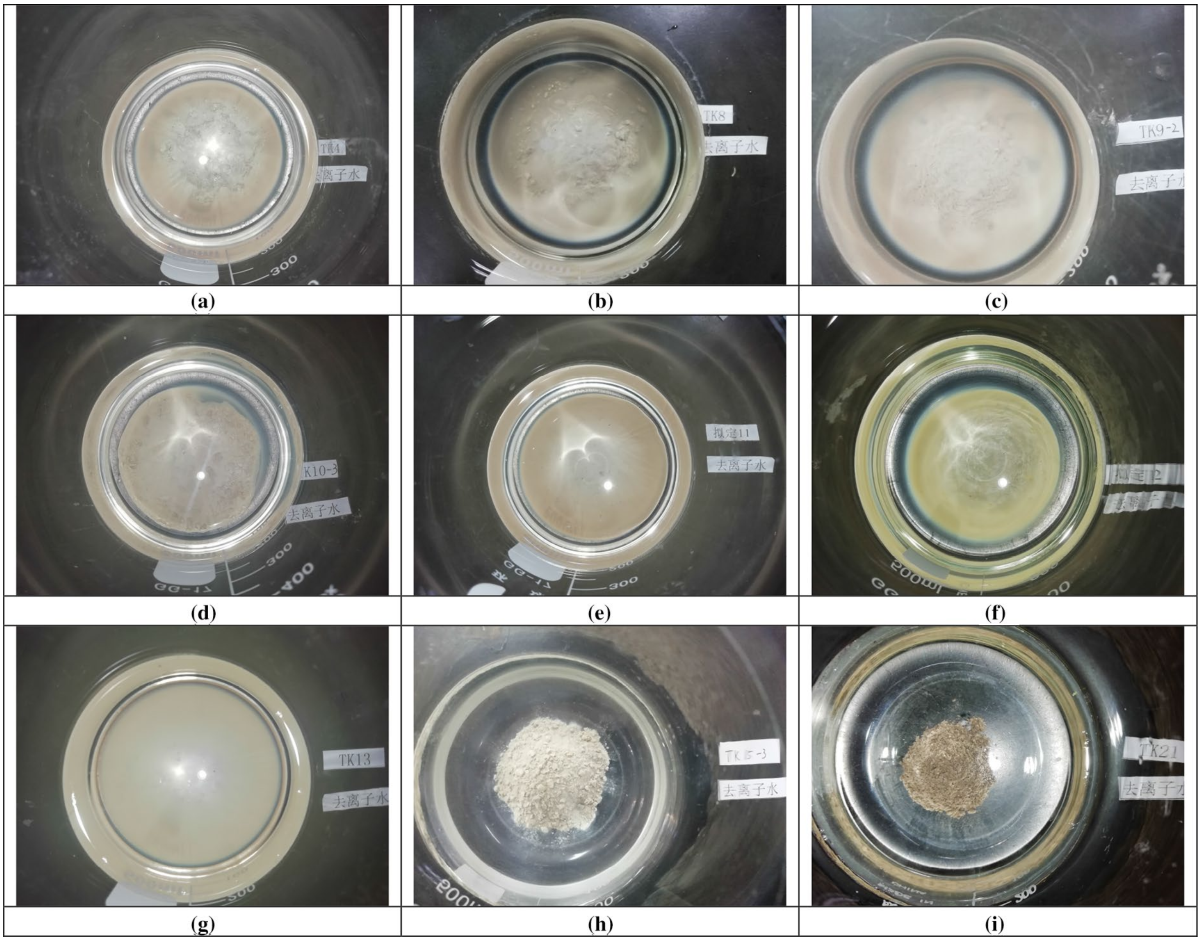

Fig. 5 Photographs of the Huaaopao soil samples after CT: **a** TK4, **b** TK8, **c** TK9, **d** TK10, **e** TK11, **f** TK12, **g** TK13, **h** TK15, **i** TK21

lead to the change of pore structure of soil, making clay particles easier to pass through the pores, which shows obvious dispersivity. Generally, the soil with clay content less than 10% is called low cohesive soil. Therefore, the reasons of dispersive characteristics can be physical, low clay contents (< 10%) and chemical, high pH values (> 9.5) and high sodium contents (PS > 60% and ESP > 7%).

The pH values of TK4, TK8, TK10–TK13, TK15 with a certain amount of clay particles (13.5 ~ 35.0%) were 9.70 ~ 10.46 (> 9.5), the PS values were 76.0 ~ 99.9% (PS > 60%) and the ESP values (ESP > 7%) were 57.1 ~ 90.6% indicated that these soil samples had conditions for chemical dispersivity. The top 7 belonged to DS and the TK 15 belonged to TS from the results of weight analysis method. The reason for the lower dispersivity of TK15 should be that its chemical dispersivity is slightly stronger than physical flocculation. It could be noticed that the clay particles content of TK9 was 8.5% (< 10%), which means it had low cohesion. And thus, the dispersivity of the TK9 came from both physical and chemical effect and of the TK4, TK8, TK10–TK13, TK15 only came from chemical effect.

Table 6 Identification results of the DHTs and chemical tests of the Huaaopao soil samples

Soil samples	DHT		PWSCT							ESPT			
	DD/ %	Results	Na^+	K^+	Ca^{2+}	Mg^{2+}	TDS	PS	Results	C_{Na+}	CEC	ESP	Results
			1/n mmol·L^{-1}					%		cmol·kg^{-1}		%	
TK4	10.3	NDS	522.17	0.22	0.11	0.32	522.82	99.9	DS	11.1	12.7	87.1	DS
TK8	14.8	NDS	308.70	0.19	0.68	7.54	317.11	97.4	DS	6.9	9.6	71.9	DS
TK9	17.6	NDS	482.48	0.25	0.98	44.65	528.36	91.3	DS	3.3	6.6	50.0	DS
TK10	28.6	NDS	538.26	0.31	0.10	0.48	539.15	99.8	DS	12.8	15.7	81.7	DS
TK11	25.4	NDS	250.00	0.13	0.20	0.15	250.48	99.8	DS	17.2	19.0	90.6	DS
TK12	25.0	NDS	413.48	0.27	0.09	0.25	414.09	99.9	DS	6.4	9.2	69.4	DS
TK13	25.7	NDS	134.78	0.10	0.39	42.16	177.44	76.0	DS	14.4	20.9	68.8	DS
TK15	30.4	TS	366.52	0.35	0.84	25.17	392.88	93.3	DS	9.1	15.9	57.1	DS
TK21	7.7	NDS	14.78	0.02	1.37	10.73	26.91	54.9	TS	0.6	17.7	3.4	NDS

3.5 Recommended Dispersivity Discrimination Order

The obvious advantage of model discrimination is fast and relatively accuracy. The weight analysis method requires longer time but more accuracy. The PT simulates the process of dispersivity destroy of cracks and is often known as the most reliable dispersivity identification test. Therefore, it accounts for a large proportion (40%) in comprehensive weight analysis method. The CT reflects the dispersivity behavior of soil in static water, the DHT quantitative describes the self dispersivity behavior of soil, and the proportions of weight analysis method are 20%, respectively. It should be noticed that the DHT is not suitable for high sodic-salts soil (ref. Fan et al. 2005). The PWSCT and ESPT could only reflect the dispersive potential according to 3.4, and the total proportions of weight analysis method is 20%. And thus, it is suggested that model identification first and laboratory tests second.

For the TK4, TK8–TK13, the DHT results were NDS and the other four test results were DS. It should be DS which is the same as the results of model discrimination and weight method. For the TK15, the ESPT and PWSCT results were DS and the other three tests results were TS. It should be TS because of same results of PT and CT. The result of comprehensive discrimination is correct, and the result of model discrimination is not perfectly correct. For the TK21, the tests except PWSCT were NDS, and it should be NDS. The result of comprehensive discrimination is correct, and the result of model discrimination is wrong. To sum up, the model discrimination had 78% accuracy and the weight analysis had 100% accuracy in this project.

3.6 Modification Effect of Different Lime Contents on the Dispersivity of Huaaopao Soil Samples

Three soil samples with dispersive characteristics were chosen to be modified by lime. A series of physical and chemical reactions occur after mixing lime with soil, such as pozzolanic reactions, exchange adsorption reactions, hydrolysis reactions and carbonation reactions, that improve the attraction between soil particles and effectively overcome the dispersivity of soil (Savaş 2016; Shoghi et al. 2017; Premkumar et al. 2017; Türköz et al. 2018; War and Thant

2019; Yao et al. 2020; Gidday and Mittal 2020). PTs and CTs were carried out on the modified soil samples because these tests have higher weighted values among the dispersivity identification tests and convenience. The results of the PTs and CTs are listed in Table 8, and photographs of the soil samples after these tests were conducted as shown in Figs. 6 and 7.

The dispersive soil samples became non-dispersive after mixing with 1–3% lime in the PT, and this phenomenon also appeared in the CT. And thus, the results showed that the dispersivity of soil samples was remarkably diminished when mixing with a certain amount of lime. Considering the difficulty in controlling and mixing the low-proportion additives and cost-effectiveness, it is suggested that the mass ratio of lime should be 1–2% in Huaaopao water hydraulic engineering.

Table 7 Identification results of weight analysis of the Huaaopao soil samples

Soil samples	Weight value/%			Comprehensive results of tests	Soil samples	Weight value/%			Comprehensive results of tests
	NDS	TS	DS			NDS	TS	DS	
TK4	20	0	80	DS	TK12	20	0	80	DS
TK8	20	0	80	DS	TK13	20	0	80	DS
TK9	20	0	80	DS	TK15	0	80	20	TS
TK10	20	0	80	DS	TK21	90	10	0	NDS
TK11	20	0	80	DS					

Table 8 Modification results of pinhole and crumb tests on the Huaaopao soil samples mixed with lime

Soil samples	Lime proportion/%	PT							CT	
		Head/mm	Test time for given head/min	Final flow rate/ml·s^{-1}	Cloudiness of flow	Hole size after test/mm	Grade	Results	Grade	Results
TK8	1	1020	5	0.2	Clear	1	ND1	NDS	1	NDS
TK11	2	1020	5	1.9	Clear	1	ND1	NDS	1	NDS
TK13	3	1020	5	1.7	Clear	1	ND1	NDS	1	NDS

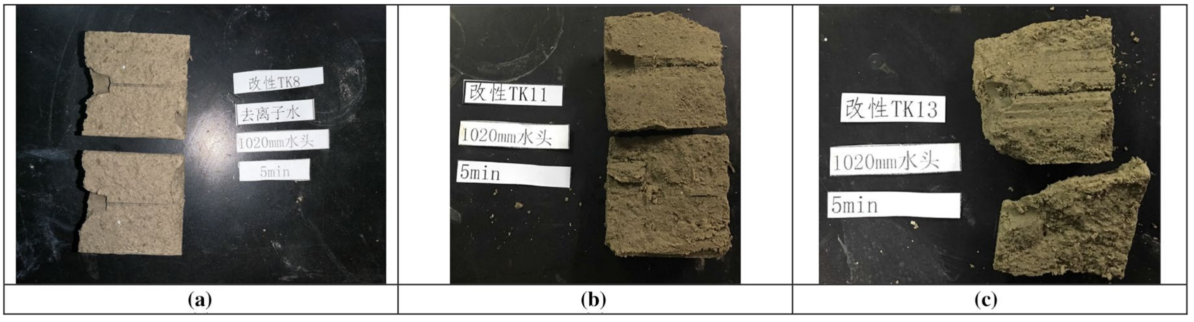

Fig. 6 Photographs of the modified Huaaopao soil samples after pinhole tests: **a** TK4, 1020-mm head, 5-min duration, **b** TK11, 1020-mm head, 5-min duration, **c** TK13, 1020-mm head, 5-min duration

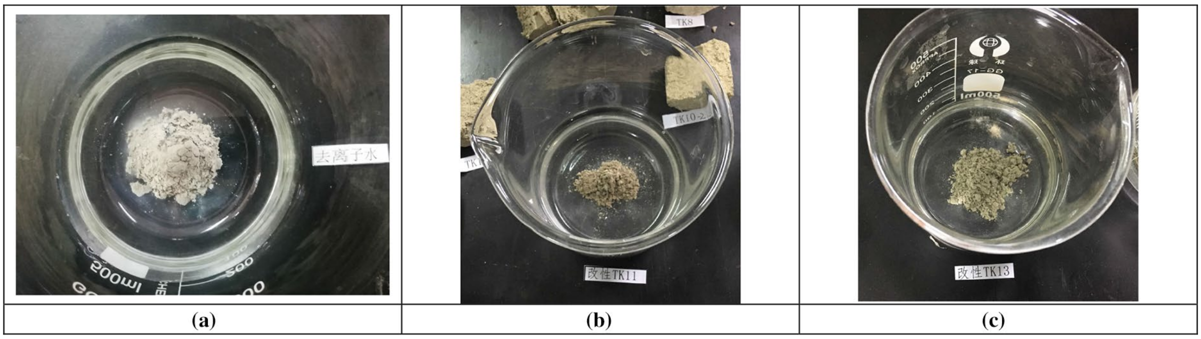

Fig. 7 Photographs of the modified Huaaopao soil samples after crumb tests: **a** TK4, **b** TK11, **c** TK13

4 Conclusions

1. Meeting the conditions of chemical dispersivity only shows that the soil sample has the potential of dispersivity. However, whether it is dispersive soil still needs to be comprehensively considered in combination with physical and dispersivity identification results.
2. The dispersivity phenomenon is obvious in Huaaopao area. The retrieved soil samples show that most of the soil samples have dispersivity, and 1 ~ 2% lime could be used to eliminate the dispersivity. It is recommended to the order of model prediction first and laboratory tests second in other engineering practices.

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Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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