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Effects of ant bioturbation and foraging activities on soil mechanical properties and stability

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ABSTRACT

Ants are ecosystem engineers, and their nesting and foraging activities are critical to modifying soil structure. In this paper, the soil physical and mechanical properties of in situ subterranean ant nesting soil and non-ant nesting soil around the nest of the *Iridomyrmex anceps* were investigated so as to evaluate the effects of activities such as nest building and foraging on soil hydrologic and stability. The results showed that ant activity increased the content of organic matter, total nitrogen and phosphorus in the soil, and decreased soil pH. The activities of ants altered the soil structure. The density, specific gravity and saturation of subsurface ant nesting soil and non-ant nesting soil showed highly significant differences, while the moisture content, dry density, pore ratio and porosity showed significant differences. The soil mechanical property tests results showed that the ant activity increased the compressibility of the soil. The ant activity reduces the resistance of soil against relative movement under the action of external force, as well as the strength of soil against axial pressure under the condition of no lateral restraint, whereas the residual strength is increased. Under low confining pressure conditions, ant presence had no significant effect on the ultimate strength of soil. However, the ultimate strength of ant nest soil was significantly lower than that of non-ant nest soil under condition of high confining pressure. These findings unveil that ant activities positively affect the energy cycle and species diversity in ecosystems but significantly reduce soil mechanical properties and stability.

1. Introduction

Within terrestrial ecosystems, ants are one of the most widely distributed organisms (Whitford et al., 2008). Ants are found in almost all terrestrial ecosystems and they account for more than 50 % of all insect populations (Benckiser, 2010), which pose the significant impacts on the community structure and function of ecosystems (Brown et al., 2012; Folgarait et al., 2002). Furthermore, ants, as excellent engineers of ecosystems, play an active role in material cycling, energy flow and evolution of soil structure in

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grassland ecosystems (Zhong et al., 2021).

At present, studies regarding the effects of ant activities on soil physicochemical properties, biological carbon cycle, and microbial properties are mainly carried out from ecological, biological, and agronomic perspectives (Nkem et al., 2000; Yang et al., 2022). According to Stadler et al. (2006) , ants could increase microbial activity in nests through direct physical action, mediated aphid infestation, accelerated litter decomposition. Through activities such as nesting and foraging, ants affected vegetation species, soil physicochemical properties and biological community characteristics of grasslands in different ways and extents (Jílková et al., 2011; Verchot et al., 2003; Zhou et al., 2020). Taylor et al. (2019) proposed that ant activity promoted the release of nitrogen from plant residues, the decomposition of organic matter, and the cycling of minerals and nutrients by decomposing plant residues. Meanwhile it increased the organic matter in the soil especially the stable humic acid, which is beneficial to the improvement of soil fertility. Moreover, ant activity can also significantly affect the soil hydrologic and structure. De Bruyn and Conacher (1990) found that the nesting activities of ants carried soil particles to form a large number of nesting channels, which effectively varied the soil structure and infiltration capacity of the soil. Eldridge (1994) used a disc permeameter to study the influence of A. barbigula nest structures on soil hydrological properties at Yathong. Steady-state infiltration under ponding (i.e. saturated-flow) on soils with the average entrances size of approximately 20 mm/min, which was four to ten times higher than the counterpart on entrance-free control soils. Other relevant studies have demonstrated that ants could clear the vegetations around their nests and affect soil hydrology through creating subsurface water-conducting macropores (voids, pipes, and corridors) and surface nest entrances to create the preferential water infiltration paths (Bétard, 2021; Frouz et al., 2003; Latchininsky et al., 2011). These findings suggest that ant activity increases soil permeability and porosity, which should be mainly attributable to interconnected channels within the nest. The increased soil permeability and porosity result in lower bulk density and more significant water infiltration into deeper soil layers, thus accelerating the soil loss. In addition, some scholars argued discovered that ant activities in dikes created an intricate anthill structure that weakened and destabilized the soil. Under the erosion of water or rain, the strength and stability of the soil presented a gradual and rapid decline (Gao and Liu, 2005; Gao and Liu, 2003). The nesting activities of ants led to complex connecting channels and anthills within the soil, which destroyed the integrity and compactness of the soil (Gabet et al., 2003). The ant nests were prone to collapse when exposed to water, significantly reducing the strength and resistance to rainwater erosion and accordingly leading to soil collapse and slope instability (Gao et al., 2011; Gao et al., 2004). In conclusion, the interaction for ant activity with thesoil structure and the hydrological properties is pronounced. The products of the ant activity could be eroded by rainwater, which posed a profound effect on the stability of the soil (Richards, 2009).

This study aims to explore the inherent relationship between ant activities and soil structure. By taking the underground ant nest soil of Iridomyrmex anceps as the research object, the effects of nesting and foraging on soil physicochemical properties were analyzed in terms of consolidation compression, shear strength, and unconfined compressive strength of soils containing ant nests. In particular, this paper emphasis on the interaction between ant activity and soil stability. More importantly, through the analysis of the ant nest system's hydraulic change characteristics, geotechnical engineering characteristics and their interactions, this study provides essential parameters for predicting the instability of soil slopes and a reference for selecting dam sites.

2. Experimental

2.1. Study region

Iridomyrmex anceps belongs to the species of Dolichoderinae and is widely distributed in coastal areas of China. *Iridomyrmex anceps* is the most common ant species in the Shanghai area. The study area is in Wetland Park, New Jiangwan City, Shanghai (31°14' N and 121°29' E). The location belongs to the subtropical monsoon climate with an average annual temperature of 16 °C and an average annual rainfall of 1200 mm. 60 % of the annual rainfall is concentrated in the flood season from May to September. The zonal vegetation is mainly evergreen broad-leaved forest and mixed evergreen deciduous broad-leaved forest. The soils are yellowish brown loam, which developed on various medium acidic crystalline rock weathering's, and weakly aluminum-rich weathered quaternary sediment parent material.

Table 1
Field data log sheet of the entrance and exit of the *Iridomyrmex anceps* nest.

No.	Number/m^2	Diameter /mm	Temperature/°C	Relative humidity/ %
1	6	2.7	25.2	61
2	5	3.2	25.1	63
3	7	2.6	25.6	64
4	10	2.5	25.4	58
5	8	2.8	25.8	68
6	11	2.5	25.5	65
7	7	2.5	24.3	57
8	5	2.7	24.8	55
9	5	3.3	24.6	54
10	8	2.6	24.2	55
11	7	2.6	24.6	55
12	6	2.9	24.7	55
Average value	7	2.74	25	59.2

2.2. Specimen preparation

The entrances and exits of the *Iridomyrmex anceps* nests are primarily distributed in places where the grass is relatively sparse and 30–50 cm away from tree roots. There are apparent anthills around the entrance and exit of the nest. The diameter of the entrance and exit is generally 2–3 mm where they often covered by plant leaves and stems. The testing environment is the temperature of 26 °C and the relative atmospheric humidity of 55 %. As illustrated in Table 1, there were four parameters record at various locations: (1) The number of entrances/exits per square meter for ant nests; (2) The diameter of entrances/exits per square meter for ant nests; (3) Temperature at the location 1 cm away from the entrances/exits; (4) Relative humidity at the location 1 cm away from the entrances/exits. It can be found that the temperature and relative humidity of different nest locations are similar.

The detailed preparation process is shown in Fig. 1. In order to avoid pulverization of the soil samples, the in-situ sealing wax technique was used to solidify the soil samples. Firstly, the soil sample is collected from newly excavated trench with depth over 1.0 m at the location more than 1.0 m from nest hole (Fig. 1(a)). After being wrapped in plastic were placed in a − 10 °C freezer for 3 days, the soil samples were cut horizontally with a thickness of 1 mm by the Digital Freezing Milling Technique (DFMT) (Fig. 1(b) and (c) Subsequently, the positions of the nests and underground passages were recorded (Fig. 1d). Finally, the 3-dimensions (3D) schematic diagrams of the ant nest were reconstructed using the computer software OpenMVG/openMVG. The depth where the nest can be obtained is within 60 cm from the surface. As per suggested by Nkem et al. (2000), the soil samples were collected in the plots at 0–10 cm depth from: (1) the top of the mound; (2) the mound perimeter; and (3) 5 m radius from the mound perimeter.

10 soil samples containing ant nests were obtained and processed by aforementioned 3D reconstruction method to determine the structural distribution of nest structure. It was reported that the influence of ant activity on soil physical and chemical properties ranged from 1 to 3 m (Dean et al., 1997). Therefore, 10 soil samples were randomly selected as control soil samples with 5 m from the center of ant nest. The sample size is 40 cm × 40 cm× 40 cm. According to the structural distribution characteristic of the ant nest, the sampling depth was in the range of 0.5–1.0 m, as shown in Fig. 2. When sampling, weeds, leaf litter and topsoil were removed from soil samples. The numbers of non-nest soil and nest soil samples were denoted as *N* and *A*, respectively. The non-ant nest soil and ant nest soil were placed in the laboratory for 5 days, and then the physicochemical characterization and mechanical geotechnical tests of soil were carried out.

2.3. Test methods

2.3.1. Physicochemical properties test

The physical characteristics of soil samples include density (ρ), dry density (ρ_d), moisture content (ω), specific gravity (Gs), void ratio (e), porosity (n) and saturation (S_r). The density, dry density, void ratio, and porosity mainly reflect the compactness of soil samples. The change of moisture content directly affects a series of mechanical properties such as consolidation compression and shear strength of soil. Specific gravity represents the mass of soil particles per unit volume. Saturation reflects the degree of pore water filling in the soil sample. The test methods for the physical characteristics of soil samples are shown in Appendix A. In addition, soil organic matter was determined using the potassium dichromate oxidation-external heating method; soil total nitrogen was determined using the Kjeldahl method; and soil total phosphorus was determined using the acid soluble-molybdenum antimony anti-colorimetric method, and the soil pH value was determined using a soil pH detector (Lufangke FK-WSYP).

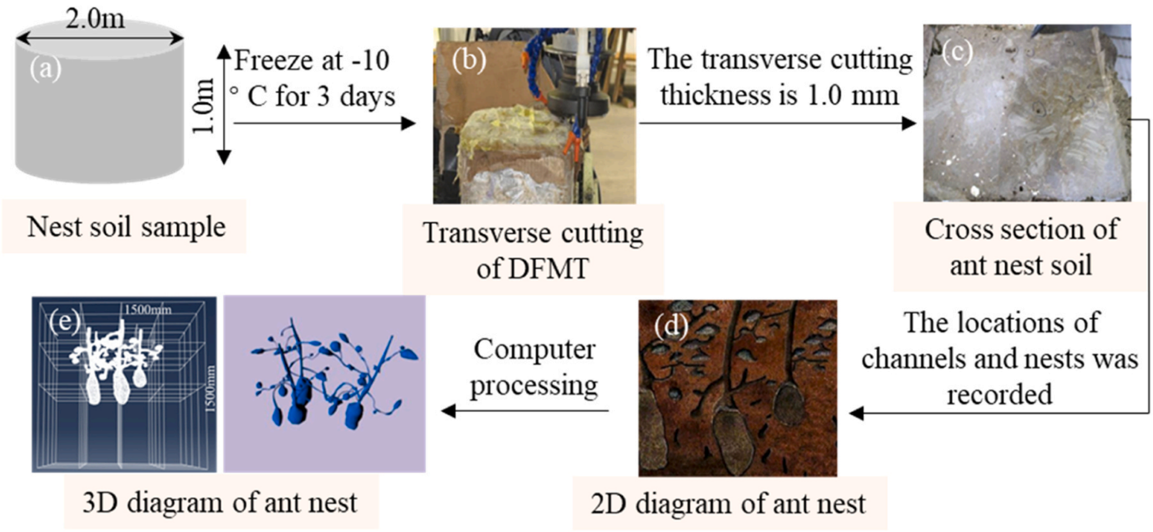

Fig. 1. Schematic diagram of ant nest structure.

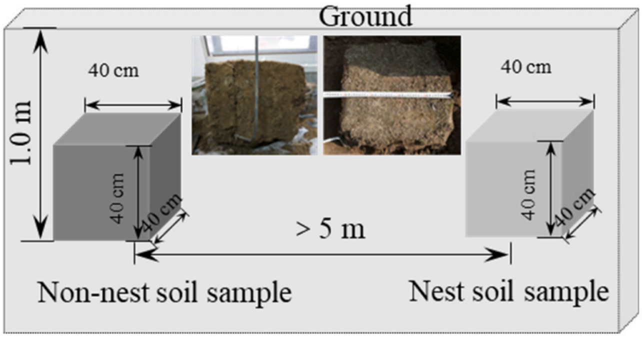

Fig. 2. Schematic diagram of soil sample collection for ant nest soil and non-ant nest soil.

2.3.2. *Consolidation compression test*

Consolidation and compression tests of soil samples were carried out in accordance with GB-T 50123–2019 (Standard for geotechnical test method). The sample is a thin cylindrical shape with a height of 2 cm and an area of 50 cm^2. The compressive deformation values of the samples were recorded after consolidation and stabilization under different levels of vertical load (25 kPa, 50 kPa, 100 kPa, 200 kPa and 400 kPa). During the springback and recompression test, the consolidation should be stable under a certain pressure, and the springback amount of the sample should be measured 24 h after each decompression. The load levels of rebound and recompression are 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa, 800 kPa, 1600 kPa and 3200 kPa. The average value was taken from 3 replicates.

2.3.3. *Triaxial compress experiment*

Triaxial compression test of soil sample was conducted in accordance with the standard GBT50123–1999 The cylindrical sample has an area of 12 cm^2 and a height of 8 cm. The samples were subjected to axial pressure (principal stress difference σ1-σ3) at different

Table 2
The physicochemical properties of non-ant nest soil and ant nest soil.

Properties	Non-nest soil	Nest soil	Parameters	DF	SS	MS	*F* Value	*P* value	Statistical significance
soil organic matter (g/kg)	12.18 ± 0.45	20.53 ± 1.58	A1	9	6.01955	0.66884	1.434	0.3	Not significant
			A2	1	348.6125	348.6125	747.39	5.68×10^{-10}	Significant
Total N (g/kg)	0.64 ± 0.05	1.45 ± 0.26	A1	9	0.047	0.00522	0.817	0.61562	Not significant
	0.86 ± 0.08	1.21 ± 0.05	A2	1	3.2805	3.2805	514.14	2.99×10^{-9}	Significant
Total P (g/kg)	5.87 ± 0.62	5.54 ± 0.072	A1	9	0.0089	9.87×10^{-4}	0.5683	0.79369	Not significant
	0.64 ± 0.05	1.45 ± 0.26	A2	1	0.6125	0.6125	352.44	1.58×10^{-8}	Significant
PH	0.86 ± 0.08	1.21 ± 0.05	A1	9	1.2672	0.1408	0.5015	0.84073	Not significant
			A2	1	0.5445	0.5445	1.94	0.19718	Not significant
Density (g/cm^3)	1.70 ± 0.002	1.59 ± 0.017	A1	9	0.0257	0.00286	1.15	0.41804	Not significant
	24.65 ± 0.56	21.36 ± 1.06	A2	1	0.05724	0.05724	23.098	0.00096	Significant
Moisture content (%)	2.74 ± 0.001	2.72 ± 0.001	A1	9	106.2645	11.80717	4.80	0.01426	Significant
	1.37 ± 0.014	1.32 ± 0.014	A2	1	54.1205	54.1205	22.03	0.00113	Significant
Specific gravity	1.01 ± 0.02	1.08 ± 0.2	A1	9	2×10^{-4}	2.22×10^{-5}	1.67	0.23	Not significant
	0.51 ± 0.006	0.524 ± 0.004	A2	1	0.00128	0.00128	96	4.24×10^{-6}	Significant
Dry density (g/cm^3)	66.8 ± 1.58	53.9 ± 2.38	A1	9	0.0221	0.00246	1.9834	0.16111	Not significant
	1.70 ± 0.002	1.59 ± 0.017	A2	1	0.013	0.013	10.50	0.01015	Significant
Void ratio	24.65 ± 0.56	21.36 ± 1.06	A1	9	0.0529	0.00588	2.1259	0.13828	Not significant
	2.74 ± 0.001	2.72 ± 0.001	A2	1	0.02245	0.02245	8.111	0.01915	Significant
Porosity	1.37 ± 0.014	1.32 ± 0.014	A1	9	0.00288	3.2×10^{-4}	1.895	0.17751	Not significant
	1.01 ± 0.02	1.08 ± 0.2	A2	1	0.00128	0.00128	7.579	0.02237	Significant
Saturation	0.51 ± 0.006	0.524 ± 0.004	A1	9	469.06	52.118	1.747	0.20938	Not significant
			A2	1	831.40	831.40	27.86	5.08×10^{-4}	Significant

Note: A1 denotes the random position of the sample; A2 denotes the sample with the presence/absence of nest; DF denotes degrees of freedom; SS denotes sum of squares; MS denotes mean squares.

constant confining pressures (100 kPa, 200 kPa, 300 kPa) until the soil sample was destroyed. The drainage condition of soil samples in consolidation and shear process is consolidated without drainage. According to Mohr coulomb strength theory, cohesion C and internal friction Angle φ of shear strength parameters, as well as cohesion C' and internal friction Angle φ' of effective shear strength parameters were obtained. The automatic triaxial compression tester (Huakan, Beijing) was used for triaxial compression test.

2.3.4. Unconfined compression test

Unconfined compression test of soil sample was also conducted in accordance with the standard GBT50123–1999 The height of the test sample is 8 cm, the diameter of the test sample is 3.91 cm, the steel ring coefficient is 246 N/mm, and the shear rate is 2 mm/min. Strain controlled unconfined pressure gauge (YYW-2, Nanjing Zhilong) was used in this test.

2.4. Mathematical statistics and analysis of experimental data

Before data analysis, normality and homogeneity of variance were tested for all data, Two-way ANOVA and least significant difference method (LSD) were used to compare differences among different data, and Origin 9.0 software was used for mapping. One assumption was made that the soils with and without ant nests were identical except for ant nesting and foraging activities.

3. Results

3.1. Physicochemical properties

The physical properties of soil are shown in Table 2. The density, specific gravity, and saturation of the two soil samples are significantly different. In comparison to non-ant nest soil ant nest soil's density and saturation decreased by 6.5 % and 19.3 %, respectively, and ant nest soil's specific gravity decreased slightly. Moisture content, dry density, void ratio, and porosity showed the significantly difference between the two soil samples. Compared with non-ant nest soil, the moisture content of ant nest soil decreased by 13.3 % and the dry density decreased, but the void ratio and porosity showed an increasing trend. In addition, there were highly significant differences in organic matter and total nitrogen content between the ant nest soil and the non-ant nest soil, and both showed the following relationships: ant nest soil > non-ant nest soil. In addition, there were significant differences in total phosphorus content and pH between the two soils. Higher total phosphorus content and lower pH values were obtained in the ant nest soil compared to the non-ant nest soil.

3.2. Consolidation compression

The extrusion of water and gas in the voids, the convergence of soil particles, and the reduction of pore volume in the soil all contribute to soil compressibility. As a result, the void and soil connection may change under external force. The void ratio-load compression curve (e-p) reflects the compressibility of soil samples under various pressures. In case the e-p curve is steeper, the compressibility of the soil is high; in case the e-p curve is flat, the compressibility of the soil is low. Each result with the error bar representing the variation of the obtained data is the average value of three tested specimens.

Fig. 3 shows the compression curves of non-ant nest soil (N-1#∼3#) and ant nest soil (A-1#∼3#). The figure shows that the curve of ant nest soil is steeper than that of non-ant nest soil during initial compression, indicating that ant nest soil has a higher

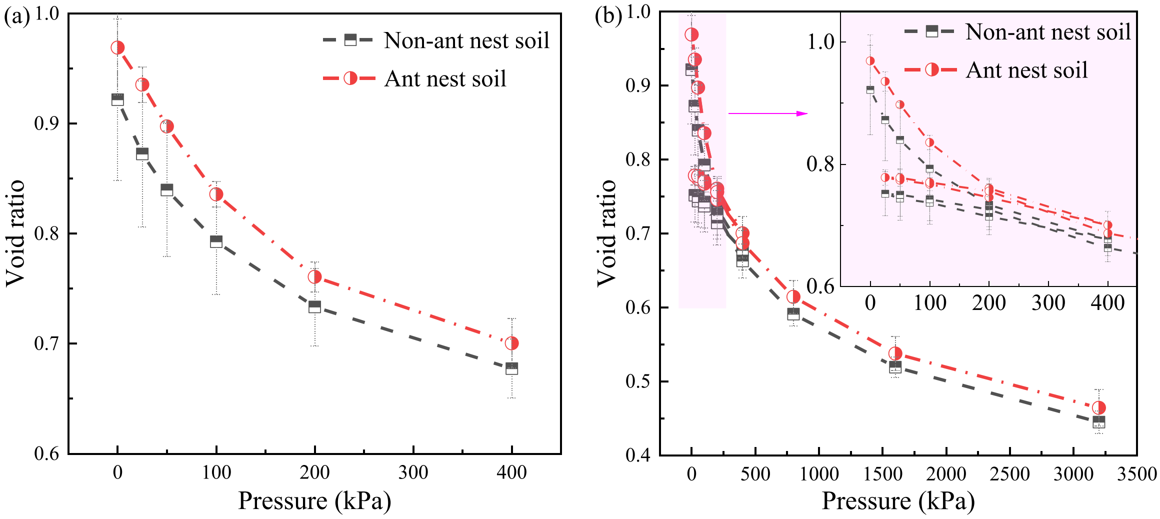

Fig. 3. The compression curves of non-ant nest soil and ant nest soil (a) The e-p compression curves, (b)The e-p rebound recompression curves.

compressibility than non-ant nest soil. The reason for this is that there are more pores and cavities in the anthill soil, the soil particles are larger, some unstable soil particles are preferentially displaced, and the pore volume decreases rapidly. With increasing pressure, the water and gas in the test pore gradually squeeze out, and the e-p curve tends to flatten. As a result, when the pressure exceeds 200 kPa, the change trends of non-ant nest soil and ant nest soil e-p curves are similar. Notably, ant nest soil had greater residual deformation during unloading than non-ant nest soil (Fig. 3b). Because of the presence of an ant nest structure, the relative displacement of ant nest soil particles between structural units, and the contact point position of soil particles, changed significantly. The soil structural units are severely damaged under external forces. However, once the external force is released, a portion of the deformation is irreversible, resulting in permanent deformation.

In Fig. 4, it is difficult to determine the point of maximum curvature of the curve due to the lack of obvious inflection points for both non-ant nest soil and ant nest soil e-lgp curves. As a result, the yield stress, or pre-consolidation pressure, of the sample cannot be determined using Casagrande's empirical drawing method (Wu et al., 2014), which is similar to the compression curve of most naturally deposited soft clay (Hong et al., 1998). In the consolidation compression test, the structural properties of the ant nest soil begin to break down from the time of loading until the load reaches the yield stress and the soil structure reaches a fully yielded state.

3.3. *Analysis of stress-strain*

The stress-strain curves of ant nest soil and non-ant nest soil under eccentric stress (σ1-σ3) are the basis for studying their strength and deformation. The (σ1-σ3)-ε1 curves of non-ant nest soil (N-4# and N-5#) and ant nest soil (A-4# and A-5#) are shown in Fig. 5.

The figure shows that under a confining pressure of 100 kPa, the expressions of the relationship curves of ant nest soil and non-ant nest soil (σ1-σ3)-ε1 are nearly identical. At the initial stage of loading the principal stress difference and axial strain are nonlinear, and as the principal stress difference increases, so does the axial strain, the ant nest soil and non-ant nest soil show obvious differences under confining pressures of 200 kPa and 300 kPa. The non-ant nest soil's principal stress difference has a nonlinear relationship with axial strain. However, the axial strain is linearly related to the principal stress difference of ant nest soil. At the same time, when the axial strain reaches 2.5 %, the ant nest soil's principal stress difference begins to exhibit a nonlinear relationship with the axial strain.

3.4. *Analysis of the relationship between ultimate strength and confining pressure*

For non-ant nest soil and ant nest soil, because the peak value of $(\sigma_1$-$\sigma_3)$-ε_1 curve is not obvious, the deviant stress $(\sigma_1$-$\sigma_3)$ corresponding to 15 % axial strain ε1 is taken as the ultimate strength of the failure point. The curves of ultimate strength (σ1-σ3)f of non-ant nest soil (N-1#~5#) and ant nest soil (A-1#~5#) versus confining pressure σ3 and the growth rate of ultimate strength are shown in Fig. 6.

The figure shows that the ultimate strengths of non-ant nest soil and ant nest soil are very close at confining pressures of 100 kPa and 200 kPa; however, at 300 kPa, the ultimate strength of ant nest soil is 13.9 % lower than that of non-ant nest soil. When the void ratio in soil decreases to a certain extent under high confining pressure, the clay particles approach each other, and the interaction force between particles increases significantly, slowing the development of ultimate strength. This is mainly manifested that as confining pressure increases from 200 kPa to 300 kPa, the rate of ultimate strength growth decreases noticeably (Fig. 6b). More importantly, when the confining pressure is increased from 200 kPa to 300 kPa, the ultimate strength of ant nest soil grows at a 40.1 % slower rate than non-ant nest soil.

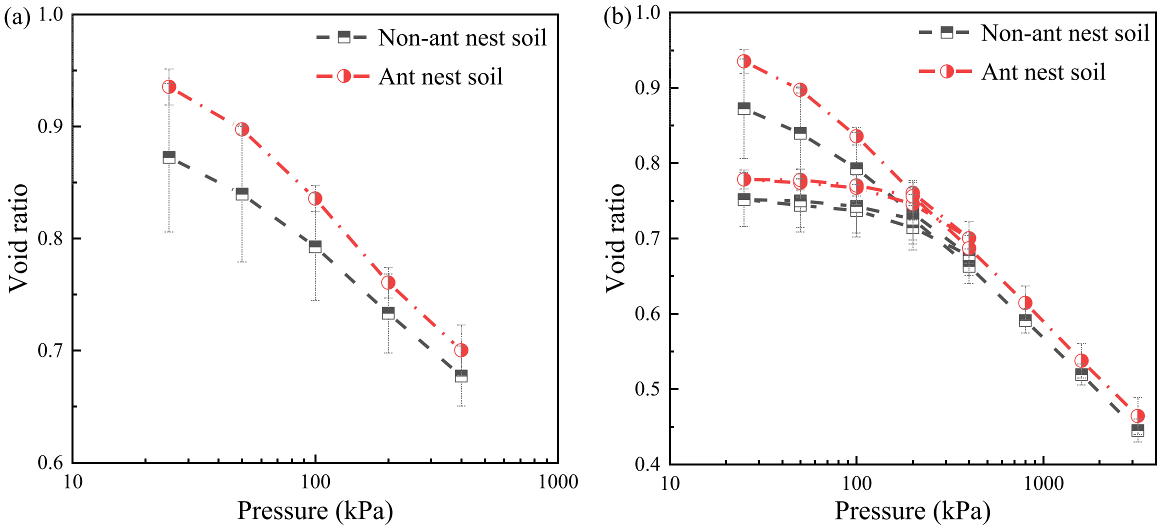

Fig. 4. The compression curves of ant nest soil and non-ant nest soil (a) The e-lgp compression curves, (b)The e-lgp rebound recompression curves.

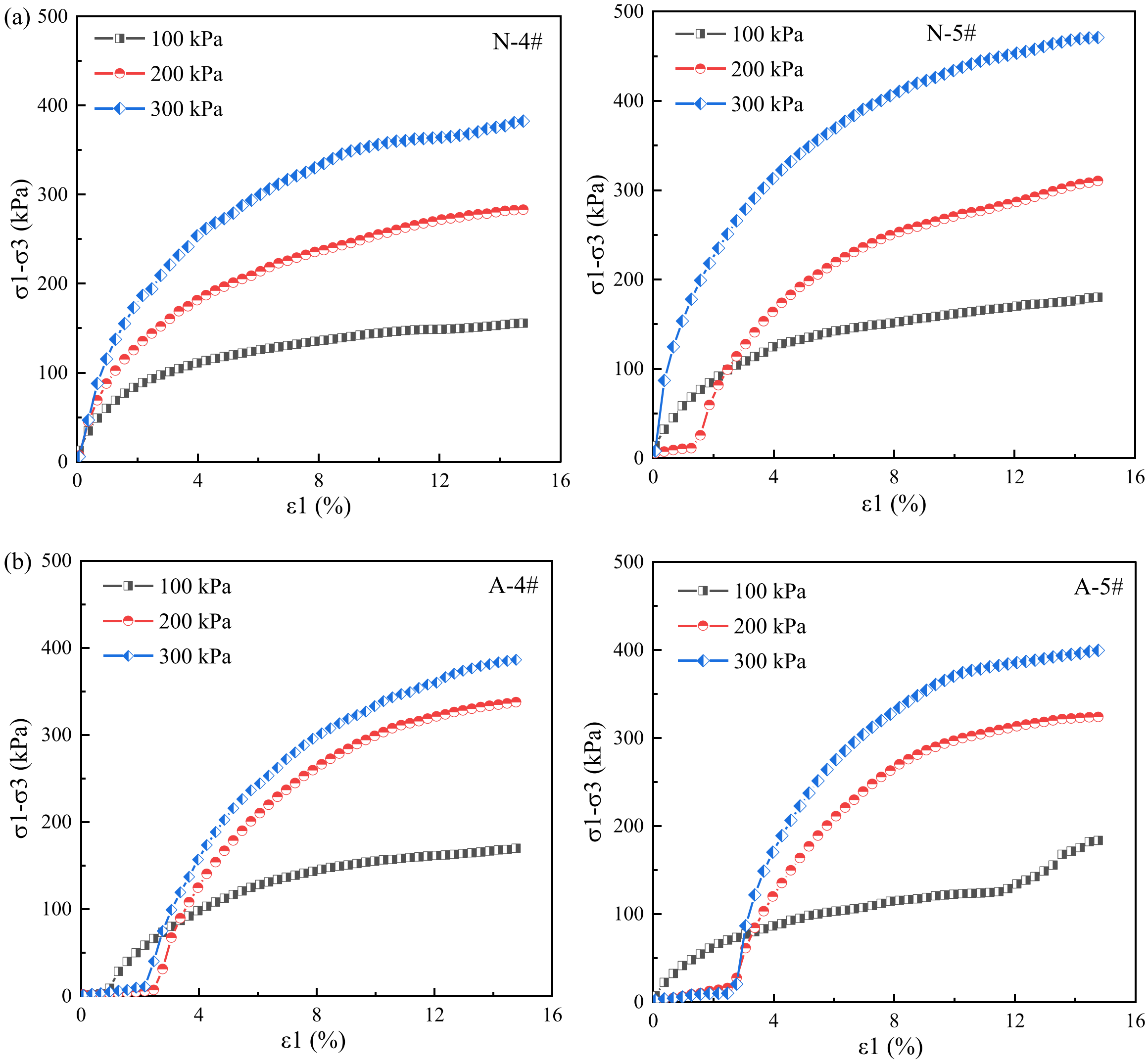

Fig. 5. The (σ_1-σ_3)-ε_1 curve under different confining pressures (a)non-ant nest soil sample and (b)ant nest soil sample.

3.5. Shear strength

The normal stress is the abscissa on the rectangular coordinate axis, and the shear stress is the ordinate. On the abscissa axis, (σ1f+σ3f)/2 as the center of the circle and (σ1f-σ3f)/2 were taken as the radius. Under the confining pressures of 100 kPa, 200 kPa and 300 kPa, the Mohr's failure stress circle and the common tangent of the Mohr's failure stress circle (i.e., the shear strength envelope) on the τ-σ stress planes of non-ant nest soil (N-6# and 7#) and ant nest soil (A-6 # and 7 #) are shown in Fig. 7. The soil cohesion C is defined as the intercept between the shear strength envelope of Mohr's failure stress circle and the ordinate, and the included angle with the abscissa is the internal friction angle φ of the soil. Under the confining pressure of 100 kPa and 200 kPa, the radius of the ultimate stress circle and the ultimate strength of non-ant nest soil and ant nest soil are similar; Under the confining pressure of 300 kPa, compared with the non-ant nest soil, the ant nest soil exhibits smaller radius of ultimate stress circle and ultimate strength, higher cohesion C and lower internal friction angle φ.

When eccentric stress (σ1-σ3) is applied under consolidated undrained conditions, pore water pressure will be generated in the soil. Therefore, the effective stress of soil is the total stress minus pore water pressure (Kimoto et al., 2011; Sun et al., 2008). The effective stress of soil is taken as the shear strength of soil, and the strength indexes include effective cohesion C' and effective internal friction angle φ'.

The effective limit stress circle and effective shear strength envelope of non-ant nest soil (N-8# and 9#) and ant nest soil (A-8# and 9#) are shown in Fig. 8. Under different confining pressures, the centre position of the effective limit stress circle of ant nest soil moves to the left along the axis, which is attributed to the lower pore water pressure in ant nest soil. The radius of the effective ultimate stress circle and the ultimate strength of the two soil samples are basically the same when confining pressure is 100 kPa; however, when

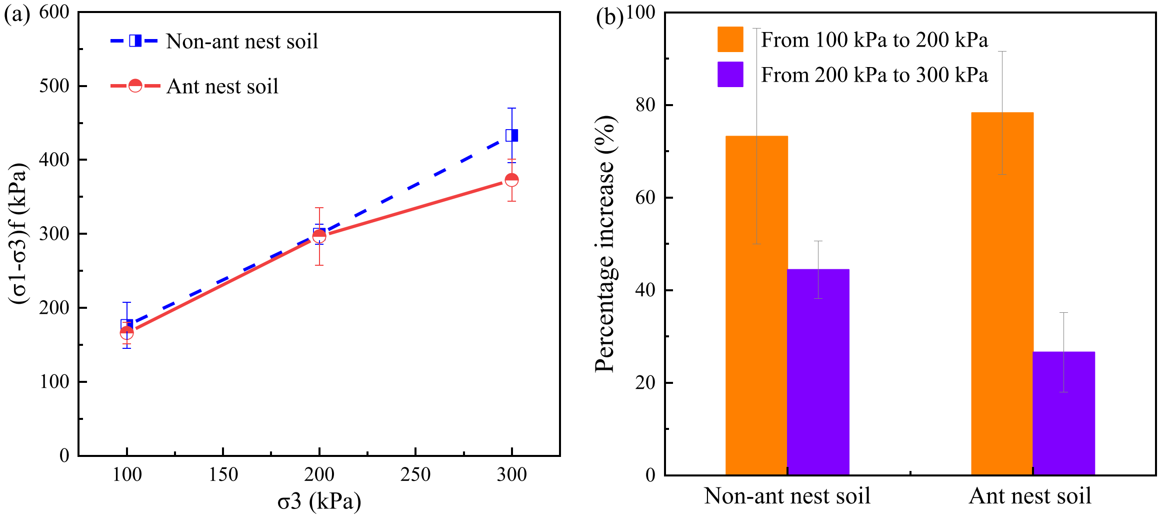

Fig. 6. (a) the relationship curve between the ultimate strength of non-ant nest soil and ant nest soil (σ1-σ3)f-σ3; (b) Growth rate of ultimate strength.

confining pressures are 200 kPa and 300 kPa, the radius of the effective ultimate stress circle and the effective ultimate strength of ant nest soil decrease. In addition, the effective internal friction angle φ' of the two soil samples is close, while the effective cohesion C' of ant nest soil decreases.

The relationship curves between pore water pressure and axial strain of non-ant nest soil (N-10#) and ant nest soil (A-10#) are shown in Fig. 9. The figure clearly shows that as confining pressure increases, the pore water pressure of the two soil samples gradually increases. Under different confining pressures, ant nest soil has lower pore water pressure than non-ant nest soil. Pore water flows primarily through the large space between adjacent flocculent soil structures and the small space between soil particles (De Magistris and Tatsuoka, 2004). The pore water pressure is higher in non-ant nest soil because the pore water dissipates through the small space between soil particles; however, the structural form of soil has changed due to ant presence, and the pore water dissipates through the large space between adjacent flocculent structures, so the pore water pressure is low.

3.6. *Unconfined compression*

The maximum axial pressure on the side of the specimen with no restrictions is defined as unconfined compressive strength. The failure surface of the soil sample occurs along the weakest part of the clay because the side of the soil sample is unrestricted. Fig. 10 depicts the axial stress-strain curves of non-ant nest soil (N-6#~10#) and ant nest soil (A-6#–10#).

The figure shows that when the axial strain (ε1) is less than 5 %, the stress of the two soil samples increases significantly with strain, and the growth rate and peak stress of ant nest soil are clearly lower than that of non-ant nest soil. Furthermore, the stress peak of non-ant nest soil is in the 6 % – 9 % strain range, whereas the stress peak of ant nest soil is in the 7 % – 10 % strain range. Notably, When the axial stress exceeds the peak value, the axial stress of the non-ant nest soil rapidly enters the descending section. In contrast, the ant nest soil has a higher residual strength. This is because the soil comes into full contact with organic materials such as plant standing dead bodies, ant secretions, and animal mucus in the ant nest soil and is compressed during the increase in stress to the peak (Stadler et al., 2006). These organic substances act as cementing agents for soil particles and intertwine with soil particles to form aggregates, resulting in good ant nest soil integrity after it reaches its ultimate strength (Zhang et al., 2020). Kandasami et al. (Kandasami et al., 2016) confirmed that ant saliva played a cementing role in the soil.

4. Discussion

4.1. *Influence of ant activities on soil physical properties*

Previous studies have shown that soils containing ant nests were normally richer in mineral and organic matter than soils without ant nests (Jiménez et al., 2008; Tuma et al., 2022). According to Hughes (1991), the soil of large, long-term stable ant nests was easier to detect the enrichment of nutrients than the soil of unstable ant nests with frequent migration. When the ant nest is abandoned, the high concentration of soil nutrients in the previous nest will slowly decreased and eventually returned to the level of no nests built. Other related studies confirmed that the enrichment of organic matter in the soil of ant nests was resulted from the nesting and foraging activities of ants, rather than the choice of ants to build their nests in soil rich in organic matter (Wagner et al., 1997). Li et al. (2003) found that the presence of yellow pier ant reduced soil bulk and moisture content, but increased soil porosity and pH value. Our results confirm that activities in the presence of ants, such as nest building and foraging, lead to changes in the physical and chemical

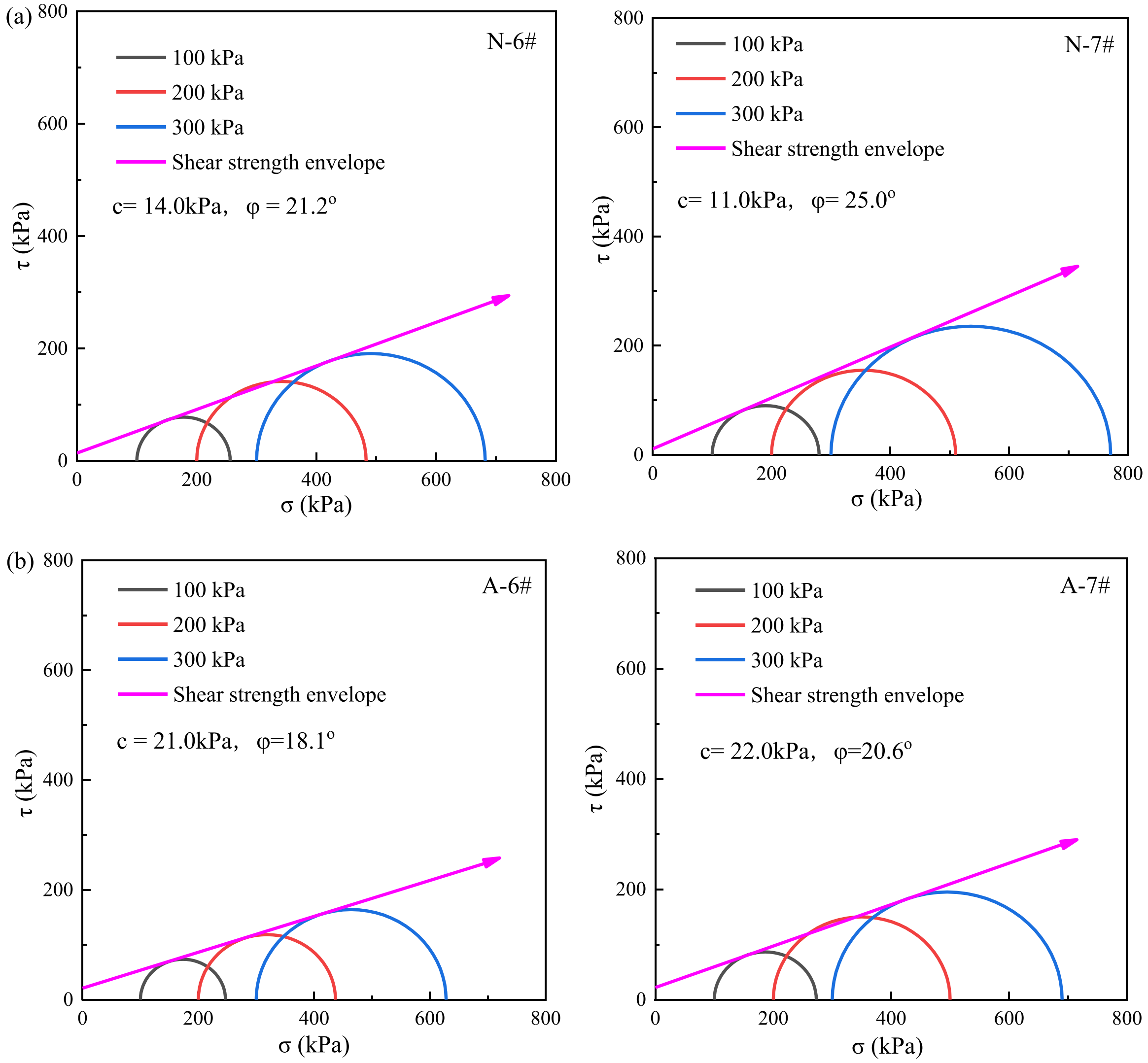

Fig. 7. Ultimate stress circle and shear strength envelope of soil(a)non-ant nest soil samples, (b)ant nest soil samples.

properties of the soil (Table 2). During the sampling and investigation process, it was found that the organic matter, N and K contents in the soil containing ant nests increased in comparison to the counterparts without ant nests. The pH of the soil containing the ant nests decreased. The main reason is that the ant nest soil contains more organic or inorganic salts, such as ant faeces, excrement, animal carcasses, and plant residues (Mandel and Sorenson, 1982). In addition, the excrement of the ants accumulates in the nest to become nutrients for the soil. Accordingly, in the material-energy cycle chain, in addition to varyingthe physical and chemical properties of the soil, ants decompose and re-release organic matter (animal and plant residues) into the soil. Therefore, ant activities play an essential role in the energy cycle and species diversity in the ecosystem (Chen et al., 2012; Lavelle et al., 2020).

In terms of the effect of ant activity on soil structure and hydrological properties. Cammeraat and Risch (2008) described the effects of ant activity on soil's physical and hydrological properties at a fine scale. The results showed that ant activity increases the porosity and decreases the bulk density of the soil. Areas with ant activity usually have higher infiltration rates. Meng et al. (2011) found that the moisture content of nest ant soil was reduced by 82.6 % compared to non-nest ant soil. The reason for this difference may be attributed to the presence of apoplectic material such as grass clippings in ant nest soil, which is loose and has a weak water retention capacity and high percolation capacity (Yu et al., 2010). Viles et al. (2021) confirmed that many influential factors including bioturbation of soil, tunnelling activity, the construction of underground chambers, galleries and macro-pores, the removal and/or accumulation of organic material, and changes in vegetation cover, might coexist and work together to modify soil infiltration characteristics. Because of their effect on soil infiltration rates, sediment provision and on vegetation cover, ants can have a profound influence on runoff and soil movement on slopes. The above results are consistent with the present study. Ant nest soil and non-ant nest soil are both silty clays, and their specific gravity changes marginally. Chen et al. (2013) also confirmed that the presence of ant reduced the soil specific gravity significantly. Ants gain living space and food by entering and leaving the soil, and their life activities

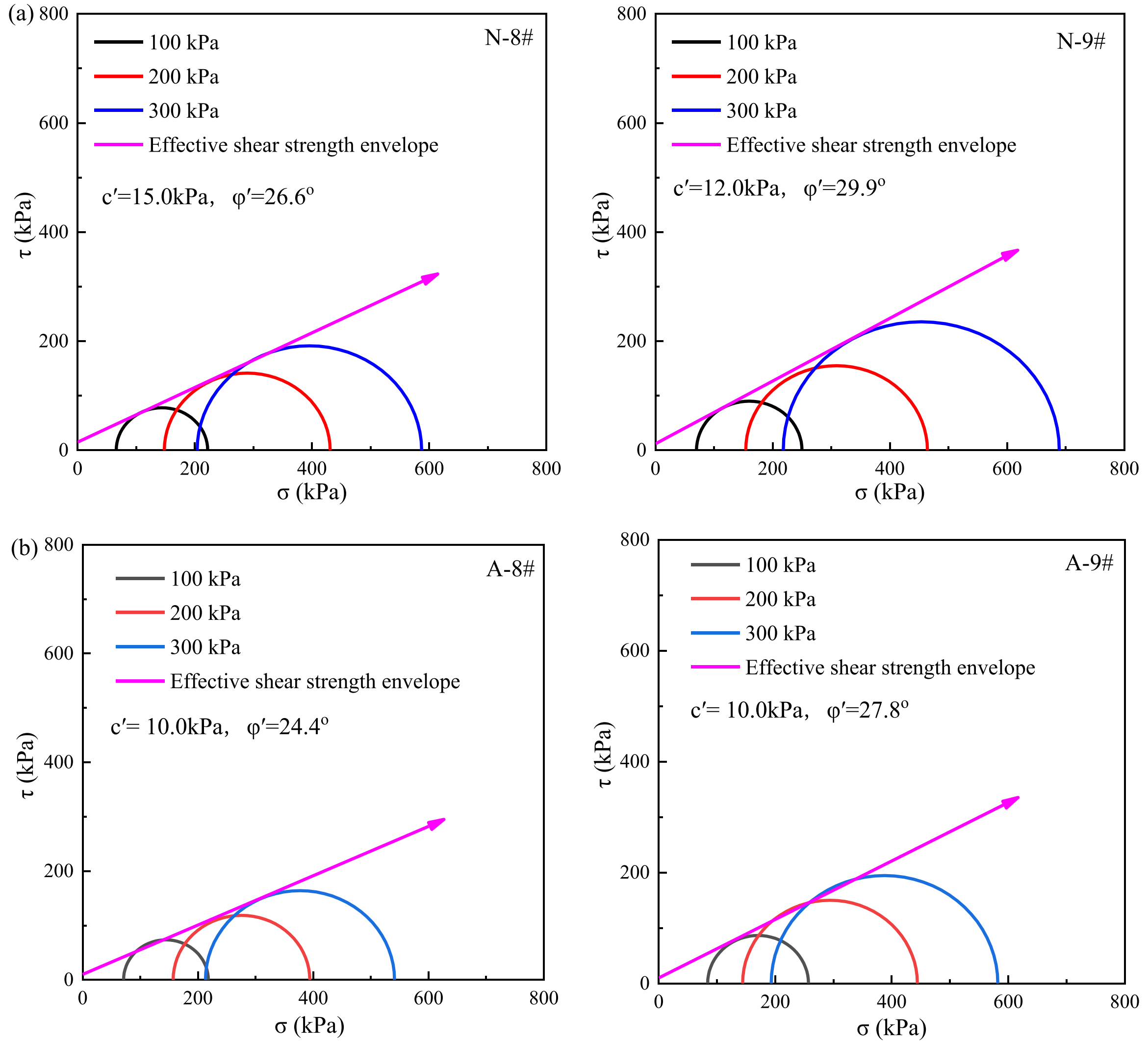

Fig. 8. effective limit stress circle and effective shear strength envelope(a)non-ant nest soil samples, (b)ant nest soil samples.

change the soil structure, forming a tubular macropore channel (Fig. 2), which increases the void ratio and porosity of the soil. According to research (Mando and Miedema, 1997), ants dig holes in the Loess Plateau of northern China to store food, survive, and reproduce, resulting in the formation of macropores. As a result, ant activity increases air permeability and water permeability in the soil, and precipitation infiltrates into the deep soil along the tunnel, lowering the moisture content of ant nest soil. Furthermore, the moisture content of ant nest soils is influenced by organic matter. Ant presence increased the content of organic matter in the soil, improving its hydrophobicity (Domisch et al., 2008). It is also worth noting that ants can transport soil in response to rainfall conditions in order to change the permeability of soil water and prevent rainfall from entering ant nests (Cerdà and Jurgensen, 2008). As a result, ant nest soil has a low moisture content and specific gravity, as well as a high void ratio. This also explains the apparently lower saturation of the anthill soil.

4.2. Influence of ant activities on soil stability properties

The effective stress in Karl Terzaghi is widely thought to determine the strength and deformation of saturated soil. The study of effective stress or stress state variables, particularly the constitutive relationship between unsaturated soil and soil, is the foundation of unsaturated soil mechanics. The shear strength of saturated soil can be expressed using the Mohr-Coulomb failure criterion as (Chen et al., 1994):

$$\tau_f = c' + (\sigma - \mu_w)\tan\varphi' \tag{1}$$

Where, τ_f is the shear stress on the damage surface, i.e., shear strength; c' is the effective cohesion; $(\sigma - \mu_w)$ is the effective normal stress

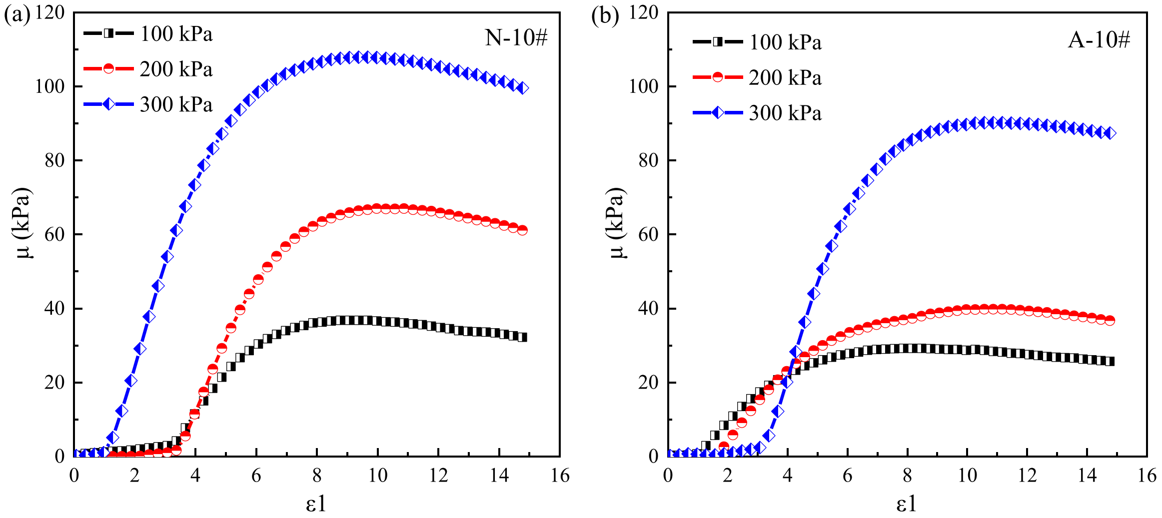

Fig. 9. Curve of Relationship between Pore Water Pressure and Axial Strain of Soil (a)non-ant nest soil sample and (b)ant nest soil sample.

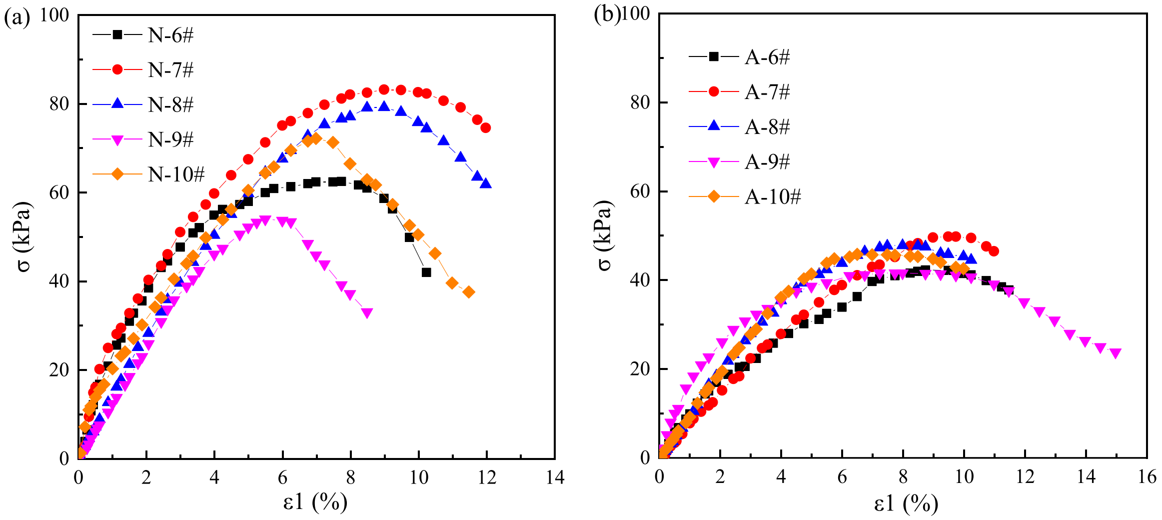

Fig. 10. curve of axial stress-strain relationship of soil (a)non-ant nest soil sample and (b)ant nest soil sample.

on the damage surface; φ' is the effective internal friction angle; $\sigma$is the normal stress on the damage surface; μ_w is the pore water pressure. For unsaturated soil, Bishop and Blight (Bishop and Blight, 1963), think that the effective stress in unsaturated soil can be expressed by

$$\sigma' = (\sigma - \mu_a) + \gamma(\mu_a - u_w) \tag{2}$$

Substituting formula (1) for formula $(\sigma - \mu_w)$(2) gives:

$$\tau_f = c' + [(\sigma - \mu_a) + \gamma(\mu_a - u_w)]\tan\varphi' \tag{3}$$

Where, σ' is the effective normal stress on the damage surface; μa is the pore air pressure; γ is the effective stress parameter. This value ranges from 0 to 1 and reflects the degree of suction contribution to effective stress. Ants participate in a variety of physical, chemical, and biological processes, including soil crushing and degradation, organic matter synthesis and decomposition, nutrient accumulation and release, dispersion and aggregation of soil colloids, and so on (Liu et al., 2011). Compared to non-ant nest soil, the number of pores and cavities increases, the indirect contact points of large-sized particles per unit volume decreases, and the stress on the contact points increases in ant nest soil, resulting in increased soil compressibility (Fig. 4) and decreased ultimate strength (Fig. 6). The void ratio of ant nest soil increased as a result of ant presence (Guangxin, 2004). Furthermore, the ant nest soil contains a high concentration of organic matter, and the hydrophilic minerals can form a thicker bound water film, causing decreased effective cohesion and effective internal friction angle (Fig. 8), resulting in a significant decrease in the soil's stability.

Although ant nest soil has a lower shear strength than non-ant nest soil, it fully demonstrates the uniqueness and superiority of the ant nest material and structure itself. Under low confining pressure, the ultimate strength of ant nest soil and non-ant nest soil is comparable in a triaxial compression test of underground ant nest soil. Furthermore, the organic matter in ant nest soil acts as a bonding agent. It enables the soil to maintain a good integrity even after reaching ultimate strength and improves the residual strength.

Nevertheless, it is also worthy noted that the effect of ants on the physicochemical properties of soil is highly dependent on the surroundings content (Wills and Landis, 2018). In fact, even the same species is capable of posing opposite effect on physicochemical properties of soil due stemmed from various habitat. The same species may increase organic matter content in one type of ecosystem and decrease it in another. Substantial different effects can be in the same ant species living in different conditions (Frouz and Jilková, 2008). For instance, Argentine ants exhibited superior survival and worker activity under warm, moist conditions compared to the hot, dry conditions (Holway et al., 2002). Xi et al. (2010) compared the effects of Red Imported Fire Ant (*lenopsis invicta*) on the physicochemical properties of soils in litchi orchard. The results evidenced that the three different regions surveyed, four different directions around the ant nest, and four different distances to the nest center presented the physicochemical properties that were significantly different from each other. Therefore, it is meant that the effects observed in this study may not be transferred to another habitat, future research should be performed in this regard.

5. Conclusion

(1) Ants, as a key component of the grassland ecosystem and consumers, alter soil physical and chemical properties through disruptive activities such as nesting and feeding, thereby influencing soil mechanical properties and stability. Based on the ecological and engineering results, the essential role of ant activities in the evolution of hydrological and structural properties in soils is discussed. The following are main findings of the present study:

(2) The mathematical statistics show that the density, specific gravity and saturation of non-ant nest soil and ant nest soil are significantly different ($P < 0.01$), while the moisture content, dry density, void ratio and porosity are significantly different ($0.01 < P < 0.05$). Ant activity reduced the density, moisture content, specific gravity, dry density, and saturation of soil, but increased the void ratio and porosity of soil. In addition, the ant nest soil had higher concentrations of organic matter, total nitrogen, and total phosphorus, as well as lower pH values.

(3) According to geotechnical engineering, ant activity improves soil compressibility; under low confining pressure conditions (100 kPa and 200 kPa), the ultimate strength of ant nest soil is similar to that of non-ant nest soil, but when the confining pressure is increased to 300 kPa, the ultimate strength of ant nest soil is significantly lower than that of non-ant nest soil. Ant nest soil had lower effective cohesion and effective internal friction angle, resulting in lower soil shear strength. Furthermore, ant activity reduces unconfined compressive strength of soil while increasing residual strength, which is attributed to the cementation of organic matter in ant nest soil to soil particles.

In addition, since the ant activities are highly dependent on the surrounding context, future research could more emphasis on the bioturbation of ants on hydrological and structural properties in soils under different context.

CRediT authorship contribution statement

Conceptualization, W.Z., P.Z., and T.C.; Data curation, M.Z., W.Z., P.Z. and Y.G.; Writing – original draft preparation, W.Z., P.Z., M.Z. and Y.G; Writing – review & editing, P.Z., W.Z. and T.C.; All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2023.e02575.

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