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Original Paper

Study on Mechanical Properties Subjected to Monotonic and Dynamic Loads of Loessal Soil in Songyuan City

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Abstract

In this paper taking loessal soil of Songyuan in Jilin province as the research object ，static and dynamic triaxial tests were conducted to investigate the effects of water content and confining pressure on dynamic characteristics of loessal soil. The test results showed that: (1) Under monotonic loading, the deformation of loessal soil exhibits two situations: strain hardening and strain softening, and the deformation behavior is influenced by water content and confining pressure. The static strength decreases with the increase of water content and increases with the increase of confining pressure. (2) The cumulative plastic strain of loessal soil under dynamic load exhibits three modes: plastic shakedown, plastic creep, and incremental collapse. Existence of critical dynamic stress results in significant differences in the cumulative plastic strain of soil. (3) The cumulative plastic strain of soil samples is influenced by water content, confining pressure, and dynamic stress amplitude, low confining pressure, high water content, and high dynamic stress amplitude are adverse to the plastic stability of loessal soil. Based on experimental results, predict the range of critical dynamic stress. The research results have reference value for the evaluation of dynamic deformation stability of settlement of subgrade constructed in the loessal soil.

Keywords

loessal soil, cumulative plastic strain, shakedown theory

1. Introduction

Located in west Jilin province, large areas of loessal soil which is rich in soluble salts distribute in Songyuan city (Sun, 2005). When the water content of the soil is low, the salts exist in the form of crystals between soil particles, playing a certain skeleton role in the soil, while loessal soil has a high bearing capacity. But under high water content conditions, the structural strength will decrease with the dissolution of soluble salts that play a cementing role in the soil, resulting in structural changes and a decrease in strength (Kong et al., 2022). The subgrade constructed in the Songyuan area inevitably involves loessal soil. Therefore, it is urgent to study the static and dynamic characteristics of loessal soil in Songyuan area.

Under cyclic loading, the deformation of the subgrade is divided into recoverable elastic deformation and irreversible plastic deformation. For practical engineering, the subgrade usually does not suddenly break down under traffic dynamic loads, but rather generated irreversible permanent plastic strain under the long-term action of traffic loads, leading to significant settlement, resulting in damage of structural, and the inability of the subgrade to continue serving. Based on the shakedown theory, Sharp (1983) and Werkmeister (2003) defined the deformation behavior of subgrade soil as plastic shakedown, plastic creep, and incremental collapse, and proposed the concept of critical dynamic stress to determine the stable state of subgrade soil under traffic loads. This theory is widely applied in design of subgrade. Wang Kangyu et al. (2021) pointed out that when the amplitude of dynamic stress is less than the critical dynamic stress, the cumulative permanent strain develops slowly, while the subgrade is in a plastic shakedown state. Liu Hailiang et al. (2022) conducted a series of dynamic triaxial tests on compacted volcanic ash, which showed that the initial stress state and dynamic load are important factors affecting the accumulation of plastic deformation in compacted volcanic ash. Low confining pressure, high dynamic stress amplitude, and high water content are not conducive to the plastic stability of compacted volcanic ash. Yi Wenni et al. (2022) conducted a study on unsaturated silt containing chloride salts, indicating that under dynamic load, when the salt content of the silt is too high, its cumulative plastic strain significantly increases.

In terms of the mechanical properties of loessal soil, Kong Fansheng et al. (2022) studied the erodibility of soda saline loessal soil through direct shear tests and scanning electron microscopy, indicating that water content is an important parameter affecting the mechanical properties of loessal soil. Therefore, this article conducted static and dynamic triaxial tests on loessal soil with different moisture contents to study the development law of cumulative permanent strain of loessal soil under long-term cyclic loading. Based on the development law of plastic strain of soil samples under different confining pressures and amplitudes, the influence of water content on the critical dynamic stress of plastic shakedown limit and plastic creep limit was analyzed, providing a theoretical basis for reasonable evaluation of the safety response behavior of loessal soil in the Songyuan area under long-term cyclic loading.

2. Materials and Methods

2.1 Sample Preparations

The samples were taken from Qian’an county, Songyuan City, Jilin Province. According to Standard for Soil Test Methods (GB/T50123-2019) (2019), The ionic content of soluble salts in the soil was determined by ion chromatography and titration. mainly with sodium ions as cations and bicarbonate ions as anions. The optimal moisture content and maximum dry density of loessal soil were determined through compaction tests. The optimal moisture content of the sample was 13.4%, and the maximum dry density was 1.871. The basic physical indexes of soil samples are shown in Table 1.

Table 1. Base Properties of the Soda-saline Loessal Soils

Parameters	Value
Natural dry density (g/cm3)	1.41
Natural water content (%)	12.84
Liquid limit (%)	32.00
Plastic limit (%)	19.30
Plasticity index PI	12.70
Optimum water content (%)	13.5
Maximum dry density(g/cm3)	1.87
Grain size distribution (%)	
Sand (≥ 50 μm)	30.52
Silt (2–50 μm)	61.22
Clay (≤ 2 μm)	8.26
Soluble salt content	
Na^+(mmol/100g)	14.22
HCO_3^-(mmol/100g)	5.56

2.2 Specimen Preparation

The samples was evenly divided into five layers and made into a cylindrical shape with a diameter of 50mm and a height of 100mm by compaction used three petal mold. The compaction factor of the specimen was taken as K = 0.95 and the actual dry density of the specimen was 1.78 g/cm^3.

3. Experimental Test Programs

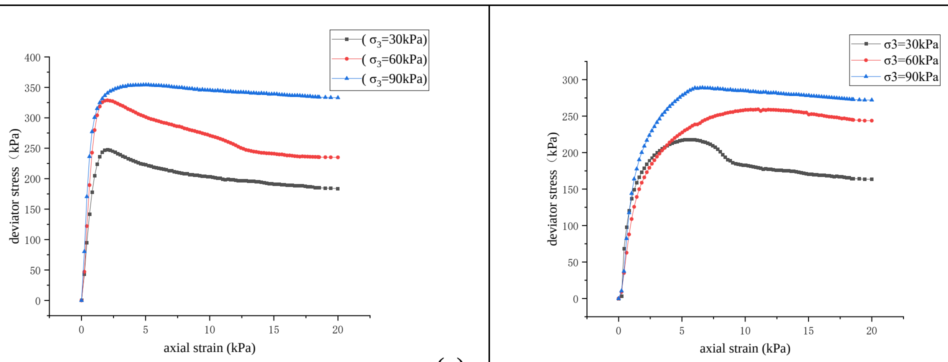
The static and dynamic triaxial tests were conducted using the GDS ELDYN dynamic triaxial instrument produced in the UK. The height and diameter of the samples was 100mm and 50mm respectively. This study considered three moisture contents of 10%, 13%, and 15%.

Because of the subgrade is often in an undrained state after compaction, consolidation undrained tests were used to study the static characteristics of soil samples, with confining pressures set at 30kPa, 60kPa, and 90kPa. In the dynamic triaxial tests, on the characteristics of the vehicle load, sine wave loads were used. And the dynamic load was loaded at a frequency of 2HZ, and according to scholars' research, the dynamic stress amplitude was set between 30kPa and 360kPa.

4. Results and Discussion

4.1 Static Characteristics

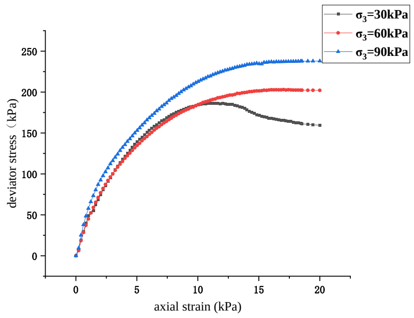
Figure 1 shows the relationship between deviator stress and axial strain under different water contents and confining pressures. The deviator stress axial strain curve showed two trends, one was strain softening type, where the deviator stress increased to a certain peak with the increase of axial strain, then gradually decreased and tends to stabilize. Another type was the continuous hardening type, where the deviator stress gradually increased with the increase of axial strain. As shown in the Figure 2, for strain softened samples, the failure mode was shear failure, with an obvious shear plane on the sample. For continuously hardened soil samples, the failure mode was bulging failure, without obvious shear plane. Table 2 shows the shear strength of samples at different confining pressures. For specimens with strain softening, the shear strength was the peak of deviator stress. For specimens with continuous hardening, the deviator stress at an axial strain of 15% was taken as the shear strength. Moisture content and confining pressure significant affected the monotonic shear characteristics of the sample. The static strength decreased with the increase of water content and increased with the increase of confining pressure. The softening phenomenon of the sample was obvious under lower confining pressure.



(a)

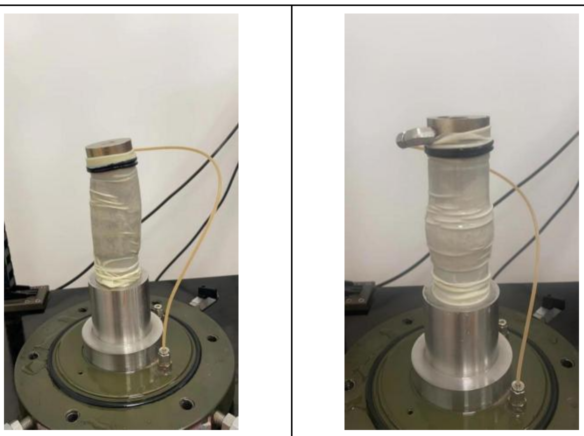
moisture content=10%

(b)moisture content=13%



(c) moisture content=15%

Figure 1. Typical Deviator Stress and Axial Strain Behavior of the Loessal Soil



(a) Shear failure (b) Bulging failure

Figure 2. Typical Failure Mode of the Loessal Soil

Table 2. Shear Strength of Loessal Soil on Different Conditions

Moisture content	deviator stress (kPa)		
	σ_3=30kPa	σ_3=60kPa	σ_3=90kPa
10%	247.2346	328.655	354.1782
13%	217.9599	259.348	282.9216
15%	185.9934	201.6867	236.2246

4.2 Dynamic Characteristics

The Figure 3 shows a schematic diagram of the variation of axial strain with vibration frequency during cyclic testing. The total strain caused by cyclic loading consists of elastic strain and permanent strain. This section focuses on discussing permanent strain.

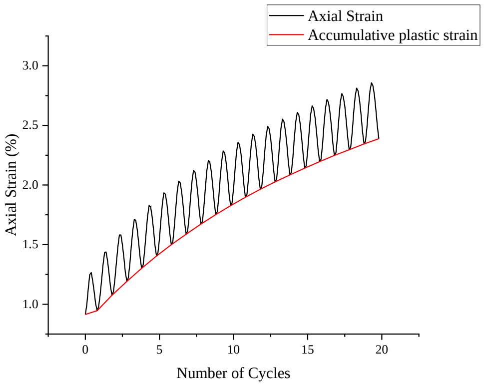


Figure 3. Schematic Diagram of the Variation of Axial Strain with Vibration Frequency during Cyclic Testing

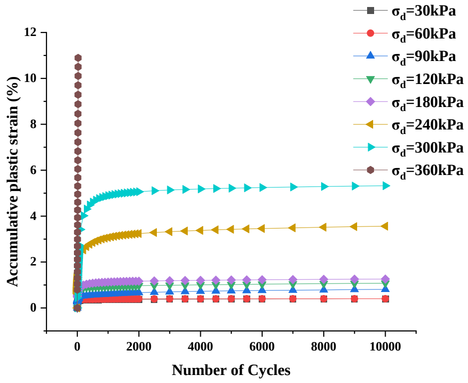
4.2.1 Effect of Dynamic Stress Amplitude

The Figures 4-6 shows the cumulative plastic strain(εp) behavior of loessal soil samples under different conditions. The results indicate that the amplitude of dynamic stress(σd) has a significant impact on the development of cumulative plastic strain. When the amplitude of dynamic stress was low, the cumulative strain of the samples increased continuously with the increase of cyclic vibration number and eventually stabilizes. As the amplitude of dynamic stress increased, the cumulative axial strain of the sample in the early stage of loading developed rapidly. As N increased, the growth rate of cumulative strain slowed down but still showed an increasing trend. Taking samples with moisture content of 13% as examples, under a confining pressure of 30kPa, while the amplitude of dynamic stress was less than or equal to 180kPa, the cumulative plastic strain did not exceed 2%. However, while the amplitude of dynamic stress was 240kPa, it reached 3%. While the amplitude of dynamic stress was 300kPa, the sample failed only after a few cycles. According to the shakedown theory proposed by Werkmeister (2003), divided the cumulative plastic strain of loessal soil samples into three modes, namely plastic shakedown (range A), plastic creep (range B), and incremental collapse (range C).

Range A: Plastic shakedown occurs when the amplitude of dynamic stress is low. In this state, the cumulative strain of the samples increase and then tend to stabilize. The cumulative strain rate rapidly decreases during the vibration process, approaching to 0, meaning that the deformation of each cycle after compaction is elastic strain.

Range B: As the amplitude of dynamic stress increase, the accumulated axial strain of the samples in the early stage of loading develop rapidly. As N increases, the growth rate of the accumulated strain slows down, and the plastic strain steadily increases, which is a plastic creep behavior.

Range C: At higher dynamic stress amplitude, the cumulative plastic strain increases rapidly and reaches the failure criterion within just a few cycles, which is incremental collapse behavior.



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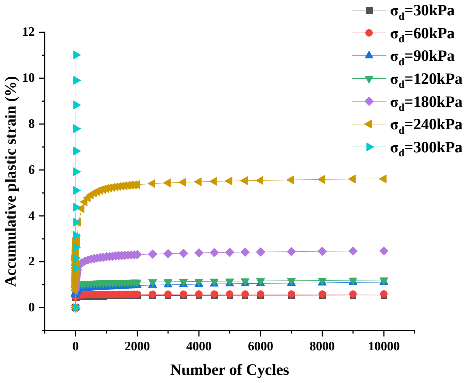

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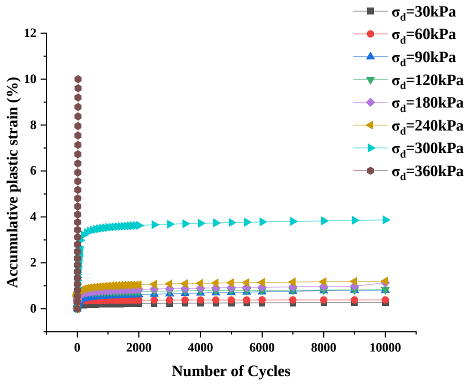

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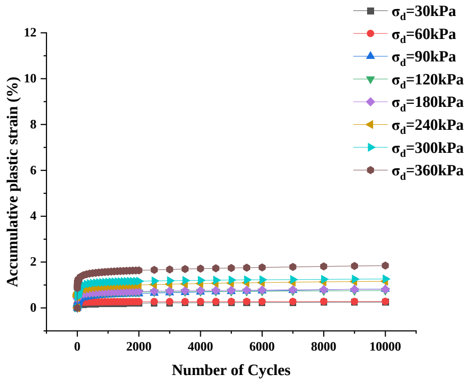
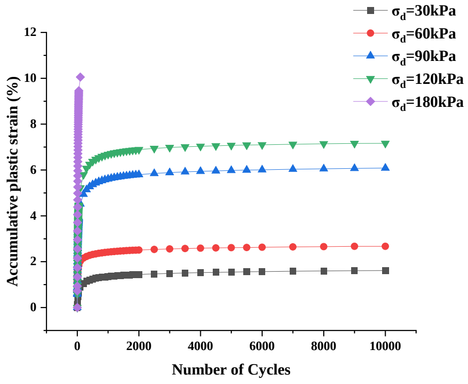


(c)

Figure 4. Accumulative plastic strains (moisture content=10%)

(a: σ_3 = 30kPa b: σ_3 = 60kPa c: σ_3 = 90kPa).



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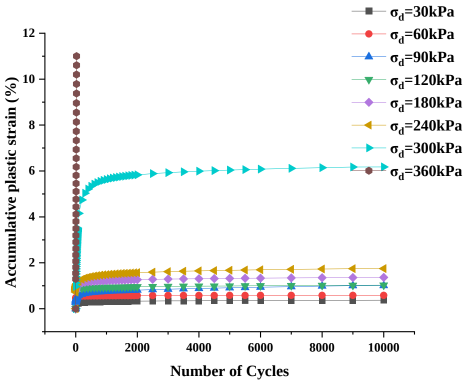

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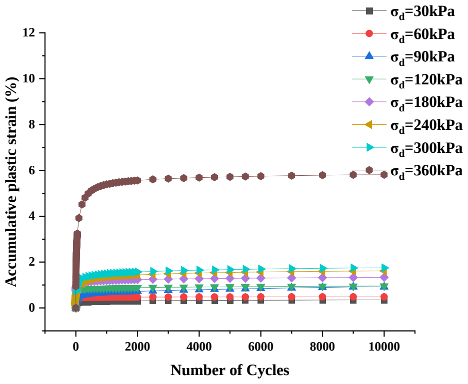
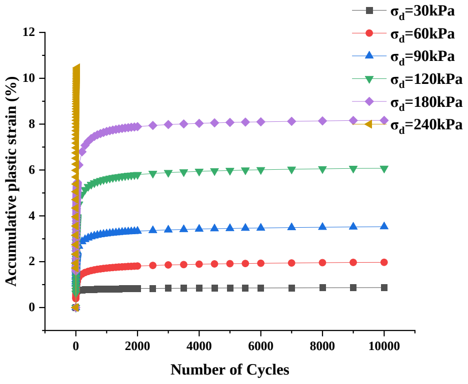


(c)

Figure 5. Accumulative Plastic Strains (moisture content=13%)

(a: σ_3 = 30kPa b: σ_3 = 60kPa c: σ_3 = 90kPa).



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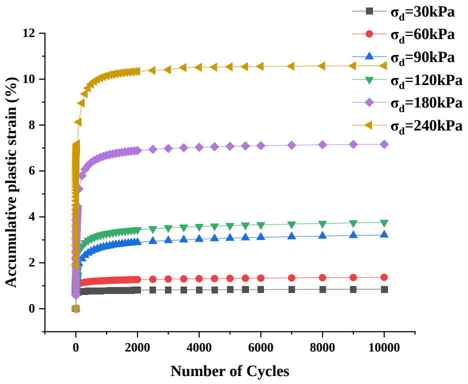

(c)

Figure 6. Accumulative Plastic Strains (moisture content=15%)

(a: σ_3 = 30kPa b: σ_3 = 60kPa c: σ_3 = 90kPa).

4.2.2 Effect of Cell Pressure

Taking samples with moisture content of 15% as examples, under a dynamic stress amplitude of 60kPa, when the confining pressures at 30kPa and 60kPa, the specimens was in plastic creep state. When the confining pressures at 90kPa, the specimens were in plastic shakedown state. It indicated that under the same dynamic stress amplitude, lower confining pressure is not conducive to the plastic stability of the subgrade material. The increase in confining pressure leaded to an increase in friction between particles, which increased the shear strength of the soil sample and subsequently affected the cumulative plastic strain of the soil sample.

4.2.3 Effect of Moisture Content

The moisture content has a significant impact on the cumulative plastic strain of loessal soil. Under the same dynamic stress, the cumulative plastic strain of soil samples with lower moisture content was lower. This result is due to the increase in water content, which thickens the water film between particles and reduces the dissolution of soluble salts that play a bonding role in the soil. As a result, the structure changes and the strength decreases (Kong et al., 2022).

4.2.4 Critical Dynamic Stress of Loessal Soil

Under cyclic loading, existence of critical dynamic stress results in significant differences in the cumulative plastic strain of soil. In theory, the critical dynamic stress is a constant value under certain conditions such as confining pressure and moisture content. However, it is difficult to accurately determine due to errors such as sample preparation differences and experimental control. However, it should be roughly within a range, so that the dynamic load applied during engineering applications can be within the allowable range. Table 3 shows the critical dynamic stress test values obtained in this experiment.

Table 3. The Critical Dynamic Stress Test Values Obtained in This Experiment

Moisture content	Cell pressure (kPa)	Plastic shakedown limit (kPa)	Plastic creep limit (kPa)
10%	30	150~180	240~300
	60	180~240	240~300
	90	240~300	>360
13%	30	90~120	150~180
	60	150~180	210~240
	90	180~210	240~300
15%	30	<30	30~60
	60	<30	60~90
	90	30~60	90~120

5. Conclusion

(1) Under monotonic loading, the deformation of loessal soil exhibits two situations: strain hardening and strain softening, and the deformation behavior is influenced by water content and confining pressure. The static strength decreases with the increase of water content and increases with the increase of confining pressure.

(2) The deformation characteristics of loessal soil in Songyuan area under dynamic load can be divided into three modes, namely plastic shakedown (range A), plastic creep (range B), and incremental collapse (range C). The dynamic response behavior of the samples was influenced by confining pressure, water content, and dynamic stress amplitude. Low confining pressure, high dynamic stress amplitude, and high water content was not conducive to the plastic stability of loessal soil.

(3) Under cyclic loading, existence of critical dynamic stress results in significant differences in the cumulative plastic strain of soil. Based on the experimental results, the approximate range of plastic stability limit and plastic creep limit can be inferred.

References

Kong, F. S., Nie, L., Xu, Y., Rui, X. J., He, Y. Y., Zhang, T., … Bao, C. H. (2022). *Effects of freeze-thaw cycles on the erodibility and microstructure of soda-saline loessal soil in Northeastern China* (p. 209). Catena. https://doi.org/10.1016/j.catena.2021.105812

Liu, H. L., Wang, C. M., Wu, D., Liu, X. Y., & Zhang, Z. M. (2022). *Deformation and critical dynamic stress for compacted volcanic ash subjected to monotonic and dynamic loads* (p. 358). Construction and Building Materials. https://doi.org/10.1016/j.conbuildmat.2022.129454

Ministry of Housing and Urban-Rural Development of the People's Republic of China. (2019). Standard for geotechnical testing method: GB/T 50123-2019[S]. Beijing: China Planning Press.

Sharp, R. (1983). *Shakedown analyses and the design of pavement under moving surface load* (Ph.D. thesis). University of Sydney.

Sun, J. Z. (2005). *Loessology*. Hong Kong Archaeological Society, Hong Kong.

Wang, K. Y., & Zhuang, Y. (2021). *Characterizing the permanent deformation Response-Behavior of subgrade material under cyclic loading based on the shakedown theory* (p. 311). Construction and Building Materials. https://doi.org/10.1016/j.conbuildmat.2021.125325

Werkmeister, S. (2003). *Permanent deformation behavior of unbound granular materials in pavement constructions* (Ph.D. thesis). Dresden University of Technology.

Yi, W. N., Liu, J. C., Yu, Q., Xuan, M. M., Liu, X. Z., Ye, X. Y., & Zhang, S. (2022). Dynamic characteristics of unsaturated salinized silt under cyclic loading. *Journal of Harbin Institute of Technology*, *55*(6).