Experimental study on deformation of heavy metal contaminated expansive soil under cyclic loading

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Abstract: Heavy metal pollution has received widespread attention at home and abroad as an important environmental engineering problem, and the research on the deformation characteristics of heavy metal contaminated expansive soil under cyclic loading is still in its infancy. According to the Nanyang expansive soil, the effects of a few factors including heavy metal ions concentration, dynamic stress amplitude, vibration frequency and confining pressure on axial cumulative deformation and critical dynamic stress for polluted expansive soil is studied. The results show that the cumulative axial strain has different development modes under different dynamic stress amplitudes, which can be divided into failure type, critical type and stable type. The same cumulative axial strain is achieved with the increase of heavy metal ion concentration, and the amplitude of dynamic stress is smaller. As the vibration frequency increases, the cumulative axial strain of the contaminated expansive soil decreases. The greater the confining pressure, the smaller the cumulative axial strain of the polluted expansive soil. The critical dynamic stress decreases with the increase of the heavy metal ions concentration, and under the same heavy metal ions concentration, the critical dynamic stress increases obviously with the increase of confining pressure.

1. Introduction

Expansive soil is widely distributed in China, with the accelerating process of urbanization and industrialization, the engineering construction of expansive soil areas suffers from serious heavy metal pollution, which leads to great changes in the properties of expansive soil[1-3]. With the rapid development of the transportation industry, a large number of highways, railways and subways have been built, and the settlement deformation of heavy metal contaminated expansive soil caused by traffic loads has been paid attention to[4]. Traffic load is a kind of dynamic load, which will produce cyclic reciprocating load, causing uneven settlement deformation, thus affecting usability and durability.

A large number of studies have been carried out by domestic and foreign scholars on the deformation characteristics of soil under polluted soil and cyclic loading[5-7]. Ratnaweera et al[8] found that the shear strength of contaminated soil decreases with the increase of heavy metal ion concentration. Liu Zhibin et al[9] studied on zinc-contaminated bentonite had showed that the decrease of clay content in contaminated soil is due to the physical and chemical interaction between
heavy metal ions and mineral particles; Qi Yusheng et al[10] conducted experimental research on heavy metal contaminated soil and found heavy metals. Ions could cause the clay content of the soil to decrease, the content of soluble salts to increase, and the unconfined compressive strength to decrease; Sakai et al[11] studied the dynamic properties of the foundation soil under different drainage conditions under traffic load; Muhanna[12] studied the deformation characteristics of soil by cyclic loading test. The results showed that the plastic deformation increases with the increase of cyclic loading times, and the cumulative deformation increases with the increase of stress level; Li xing et al[13] studied the dynamic characteristics of cement modified expansive soil under the dry-wet cycle, and found that adding cement and increasing confining pressure could significantly enhance the ability of the improved soil to resist the dry-wet cycle. Yin song et al[14] explored the influence of factors such as water content, confining pressure and dynamic stress amplitude on test results by studying the deformation characteristics of residual soil compacted under cyclic loading.

The above studies are all about the basic properties of heavy metal contaminated soil or the characteristics of uncontaminated soil under cyclic loading. The research on the deformation characteristics of heavy metal contaminated expansive soil under cyclic loading is relatively rare. The research is to analyze the traffic load. The settlement deformation of heavy metal contaminated expansive soil has certain theoretical and engineering significance.

2. Test materials and methods
Soil was taken from shigang town, neixiang county, nanyang city, henan province, with a depth of 2m and a maroon color. The basic physical properties of soil were measured, as shown in table 1. Lead nitrate (Pb(NO₃)₂) and zinc nitrate hexahydrate (Zn(NO₃)₂·6H₂O) were selected as soil pollutants.

| Moisture content (%) | Dry density (g/cm³) | Proportion Limit (%) | Plastic Limit (%) | Optimum moisture content (%) | Maximum dry density (g/cm³) | Free expansion rate (%) |
|----------------------|---------------------|----------------------|-------------------|-----------------------------|-----------------------------|------------------------|
| 25.31                | 1.38                | 2.68                 | 48.8              | 28.33                       | 1.54                        | 58                     |

The selected lead and zinc ion concentrations (the ratio of ion mass to dry soil mass) respectively are 0 mg/kg, 1000 mg/kg, 5000 mg/kg, and 10000 mg/kg, and the heavy metal ion compound is dissolved in the distilled water. In the solution, and over 2mm sieve dry soil mix evenly, divided into five layers into the diameter of 39.1mm, high 80mm mold, so that the sample is uniformly compacted and has the same compaction degree, and then the soil sample vacuum saturation.

In terms of dynamic loads, there are irregular waveforms and regular waveforms such as rectangular waves, triangular waves, sine waves, and the like. The sine wave load is conservative, convenient and practical, and it is dominant in soil dynamics research[15]. In this test, a microcomputer-controlled electro-hydraulic servo-turbine triaxial instrument is used, and the dynamic load waveform used is a sine wave. After the soil sample is consolidated under a certain confining pressure, dynamic stress is applied under undrained conditions. The termination condition of the cyclic loading is the number of cyclic loadings (10000 times) or the maximum dynamic strain (15%).

3. Test results and analysis
3.1. Dynamic stress amplitude influence
The dynamic stress amplitude refers to the magnitude of the vibration load and is an important factor affecting the dynamic characteristics of the soil. The test takes the same vibration frequency and confining pressure. Under different dynamic metal stress concentrations of different heavy metal ions,
the experimental scheme 1 is shown in Table 2, and the influence of dynamic stress amplitude on the axial cumulative strain of heavy metal contaminated expansive soil is analyzed.

| Group No | Heavy metal ion concentration (mg/kg) | Confining pressure (kPa) | Frequency (Hz) | Dynamic stress amplitude (kPa) |
|----------|--------------------------------------|--------------------------|----------------|-------------------------------|
| 1        | 0                                    |                          |                | 120, 130, 140, 150, 160       |
| 2        | 1000 (Pb^{2+})                       |                          |                | 105, 115, 125, 135, 145       |
| 3        | 5000 (Pb^{2+})                       |                          |                | 90, 100, 110, 120, 130        |
| 4        | 10000 (Pb^{2+})                      | 50                       | 1              | 80, 90, 100, 110, 120         |
| 5        | 1000 (Zn^{2+})                       |                          |                | 110, 120, 130, 140, 150       |
| 6        | 5000 (Zn^{2+})                       |                          |                | 95, 105, 115, 125, 135        |
| 7        | 10000 (Zn^{2+})                      |                          |                | 85, 95, 105, 115, 125         |

Figure 1. The relationship curves of cumulative axial strain-vibration frequency under different dynamic stress amplitudes

(a) Remolded soil
(b) 5000mg/kg Pb^{2+} ion
(c) 5000mg/kg Zn^{2+} ion
Figure 1(a), (b) and (c) are the curves of cumulative axial strain and vibration times of remolded soil, 5000mg/kg Pb²⁺, 5000mg/kg Zn²⁺ under different dynamic stress amplitudes, respectively. According to the curve, under different dynamic stress amplitudes, the cumulative axial strain has different development patterns with the increase of the number of vibrations. According to the development form, it can be divided into destructive, critical and stable. The dynamic stress amplitude corresponding to the critical curve is the critical dynamic stress, which is the maximum dynamic stress amplitude that does not cause the damage of heavy metal contaminated expansive soil. As the dynamic stress amplitude less than the critical dynamic stress, the deformation rate decreases with the increase in the number of cyclic vibrations. As a certain number of times (1000 times) is reached, the cumulative axial strain eventually tends to be stable. When the dynamic stress amplitude is larger than the critical dynamic stress, the cumulative axial strain increases rapidly with the increase of the number of vibrations, and the damage is achieved when the number of vibrations is small (100 times). The study of the critical dynamic stress of heavy metal contaminated expansive soil and Matsui[16], Zhou Jian[17] and other stress-controlled cyclic dynamic triaxial tests found that the threshold stress of the threshold is consistent with the conclusion.

From Figure 1. (a), the critical dynamic stress of remolded soil is 140 kPa, and Figure 1. (b) 5000mg/kg Pb²⁺ critical dynamic stress is 110 kPa. Figure 1. (c) 5000mg/kg Zn²⁺ critical dynamic stress is 115 kPa, 1000mg /kg Pb²⁺, 1000mg/kg Zn²⁺, 10000mg/kg Pb²⁺, 10000mg/kg Zn²⁺. The cumulative axial strain-vibration times curve under different dynamic stress amplitudes is similar to Figure 1. (a)(b)(c). When the pressure is 50 kPa and the vibration frequency is 1 Hz, the number of vibrations is the same as the concentration of heavy metal ions increases, and the same cumulative axial strain is reached, and the dynamic stress amplitude is smaller. When the Pb²⁺ ion concentration is the same as the Zn²⁺ ion concentration and the number of vibrations, the same cumulative axial strain is achieved, and the lead-contaminated expansive soil has a smaller dynamic stress amplitude than the zinc-contaminated expansive soil.

3.2. Vibration frequency effect
The test takes the same values of confining pressure and dynamic stress. Under different vibration frequencies of different heavy metal ion concentrations, the experimental scheme 2 is shown in Table 3. The influence of vibration frequency on the axial cumulative strain of heavy metal contaminated expansive soil is analyzed.

| Group No | Heavy metal ion concentration (mg/kg) | Confining pressure (kPa) | Frequency (Hz) | Dynamic stress amplitude (kPa) |
|----------|--------------------------------------|-------------------------|----------------|-------------------------------|
| 1        | 0                                    |                         |                |                               |
| 2        | 1000 Pb²⁺                            |                         |                |                               |
| 3        | 5000 Pb²⁺                            |                         |                |                               |
| 4        | 10000 Pb²⁺                           | 50                      | 0.5            | 100                           |
| 5        | 1000 Zn²⁺                            |                         |                |                               |
| 6        | 5000 Zn²⁺                            |                         |                |                               |
| 7        | 10000 Zn²⁺                           |                         |                |                               |
| 8        | 0                                    |                         |                |                               |
| 9        | 1000 Pb²⁺                            | 50                      | 1              | 100                           |
| 10       | 5000 Pb²⁺                            |                         |                |                               |
11 10000 (Pb²⁺)
12 1000 (Zn²⁺)
13 5000 (Zn²⁺)
14 10000 (Zn²⁺)
15 0
16 1000 (Pb²⁺)
17 5000 (Pb²⁺)
18 10000 (Pb²⁺)  50  2  100
19 1000 (Zn²⁺)
20 5000 (Zn²⁺)
21 10000 (Zn²⁺)

(a) 5000mg/kg Pb²⁺ ion  
(b) 5000mg/kg Zn²⁺ ion

Figure 2. The relationship curves of cumulative axial strain-vibration frequency under different vibration frequencies

(a) Pb²⁺ ion  
(b) Zn²⁺ ion

Figure 3. The relationship between cumulative axial strain-heavy metal ion concentration under different vibration frequencies
Figure 2 (a) (b) is the 5000mg/kg Pb^{2+}, 5000mg/kg Zn^{2+} cumulative axial strain and the number of vibrations at different frequencies of the relationship curve. 1000mg/kg Pb^{2+}, 1000mg/kg Zn^{2+}, 10000mg/kg Pb^{2+}, 10000mg/kg Zn^{2+} accumulate axial strain at different vibration frequencies and the relation curve of the number of vibrations is similar. Under the same vibration frequency, the cumulative axial strain decreases with the increase of the vibration frequency; As the number of vibrations increases, the cumulative axial strain increases rapidly and then the increasing rate gradually decreases. When the vibration frequency is small, the cumulative axial strain decreases. It increases faster with the number of vibrations.

Figure 3 (a) (b) is in the confining pressure of 50kPa, the dynamic stress amplitude of 100kPa, the number of vibrations 10,000 times, respectively, at different vibration frequency under the cumulative axial strain and Pb^{2+}, Zn^{2+} ion concentration relationship curve. With the increase of the concentration of heavy metal ions, the axial cumulative strain is also increasing, and under the same heavy metal ion concentration, the lead-contaminated expansive soil has greater axial cumulative strain than that of zinc-contaminated expansive soil.

3.3. Confining pressure effect

The vibration frequency and dynamic stress amplitude of the test are the same, and the confining pressure of different heavy metal ion concentrations from 50 kPa is increased to 100 kPa. As shown in Table 4, Test Scheme 3 analyses the influence of confining pressure on the axial cumulative strain of heavy metal contaminated expansive soil.

| Group No | Heavy metal ion concentration (mg/kg) | Confining pressure (kPa) | Frequency (Hz) | Dynamic stress amplitude (kPa) |
|----------|-------------------------------------|------------------------|---------------|--------------------------------|
| 1        | 0                                   |                        |               | 170, 180, 190, 200, 210        |
| 2        | 1000 (Pb^{2+})                      |                        |               | 165, 175, 185, 195, 205        |
| 3        | 5000 (Pb^{2+})                      |                        |               | 150, 160, 170, 180, 190        |
| 4        | 10000 (Pb^{2+})                     | 100                    | 1             | 140, 150, 160, 170, 180        |
| 5        | 1000 (Zn^{2+})                      |                        |               | 160, 170, 180, 190, 200        |
| 6        | 5000 (Zn^{2+})                      |                        |               | 155, 165, 175, 185, 195        |
| 7        | 10000 (Zn^{2+})                     |                        |               | 145, 155, 165, 175, 185        |
Figure 4. The relationship curves of cumulative axial strain-vibration frequency under different dynamic stress amplitudes

Figure 5. The relationship between critical dynamic stress and heavy metal ion concentration under different confining pressures

Figure 4. is a relationship between the axial strain and the number of vibrations at a confining pressure of 100kPa with different dynamic stress amplitude. Similar to Figure 4, the 1000mg/kg Pb\(^{2+}\), 1000mg/kg Zn\(^{2+}\), 10000mg/kg Pb\(^{2+}\), 10000mg/kg Zn\(^{2+}\) are used. Combined with Figure 1, it can be analyzed that the amplitude of dynamic stress is the same, the greater the confining pressure, the smaller the cumulative axial strain under the same vibration times. Figure 5 is the relationship between critical dynamic stress and heavy metal ion concentration under different confining pressures. With the increase of heavy metal ion concentration, the critical dynamic stress decreases continuously; At the same time of heavy metal ion concentration, the confining pressure increases, the critical dynamic stress increases obviously, and the zinc-contaminated expansive soil is larger than the critical dynamic stress of lead-contaminated expansive soil.

It can be seen that after the expansive soil is polluted by heavy metal ions (Pb\(^{2+}\), Zn\(^{2+}\)), the internal equilibrium conditions between the expansive soil are broken, and the electric field and interconnection on the surface of soil particles are changed, thus the accumulated axial strain and critical dynamic stress of contaminated expansive soil are changed.
4. Conclusion

Through the experimental study on the deformation characteristics of heavy metal contaminated expansive soil under cyclic loading, the influences of heavy metal ion concentration, dynamic stress amplitude, vibration frequency and confining pressure on cumulative axial strain and critical dynamic stress of heavy metal contaminated expansive soil are obtained.

(1) Under different dynamic stress amplitudes, the cumulative axial strain has different development trends, which can be divided into fracture type, critical type and stable type. When the confining pressure, vibration frequency and vibration frequency are the same, as the concentration of heavy metal ions increases, the same cumulative axial strain is reached, and the dynamic stress amplitude is smaller.

(2) When the confining pressure, dynamic stress amplitude and vibration frequency are the same, the cumulative axial strain of the contaminated expansive soil decreases with the increase of the vibration frequency. As the concentration of heavy metal ions increases, the axial cumulative strain also increases.

(3) When the vibration frequency, dynamic stress amplitude and vibration frequency are the same, the larger the confining pressure, the smaller the cumulative axial strain of the contaminated expansive soil. As the concentration of heavy metal ions increases, the critical dynamic stress decreases continuously. When the concentration of heavy metal ions is the same, the confining pressure increases and the critical dynamic stress increases significantly.

Acknowledgments

Project supported by the National Natural Science Foundation of China(U1204511)(51509274), Project of Subsidized Youth Backbone Teachers in Henan Higher Education Institutions(2013GGJS-118), Key Scientific Research Projects of Universities in Henan(19A560027),thank you for all those who give, support and help this research. Thank you very much.

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