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NUMERICAL SIMULATION ON DYNAMIC DEFORMATION CHARACTERISTICS OF LIGHT WEIGHT SOIL WITH DIFFERENT EPS PARTICLE SIZES BY DISCRETE ELEMENT METHOD

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ABSTRACT

In order to explore the influence laws of EPS (Expanded Polystyrene) particle sizes on the dynamic deformation characteristics of light weight soil, under the conditions of 15% cement content and 50% EPS particles volume ratio, indoor dynamic triaxial tests of light weight soil with EPS particle sizes of 1 ~ 3 mm, 3 ~ 5 mm, and 5 ~ 6 mm are carried out. Light weight soil numerical models are established by using the PFC3D discrete element software, and the micro mechanical properties of light weight soil with different EPS particle sizes are discussed from two aspects of contact force and displacement field. The results show that as EPS particle sizes increases, the weak contact surface between EPS particles and solidified soil particles increases, and stress concentration is easy to occur. The dynamic strength of light weight soil decreased by 5.75% ~ 20.04% and 7.06% ~ 34.96% with the increasing of EPS particle sizes from 1 ~ 3 mm to 3 ~ 5 mm and 5 ~ 6 mm, respectively. The contact force between EPS particles and soil particles is smaller than that between soil particles in the numerical models. With the increasing of the loads, the contact force of particles increases, and the particles move from the two ends to the middle. With the increasing of EPS particle sizes, the distributions of contact force are more uneven, the specimens are easier to be destroyed, and the displacement field is asymmetrical. However, the displacement interface gradually moves to the middle position with the increasing of loads. It is consistent with the laws that the macroscopic dynamic strength of light weight soil decreases with the increasing of EPS particle sizes.

Key words: Light weight soil, EPS particle sizes, dynamic deformation characteristics, hysteresis curve, discrete element method, mesoscopic mechanism.

1. INTRODUCTION

With the comprehensive popularization of infrastructure, the higher requirements of civil engineering on material properties are put forward (Hou *et al.* 2011). Expanded Polystyrene (EPS) particles light weight soil as a new type of geosynthetics, it is made from raw soil, cement, EPS particles and water. Because of its advantages of light weight, higher strength, good self-reliance and simple construction technology, it is widely used in road, railway subgrade and abutment backfilling engineering (Hou and Xu 2009; Hou 2012; Hou *et al.* 2020). As a kind of filling material, the engineering properties of light weight soil is undoubtedly influenced by EPS particle sizes, density and other physical properties. And traffic, earthquake and other dynamic loads will cause certain damage to light weight soil, and then endanger the use of engineering facilities (Hou 2015; Li *et al.* 2017; Chenari *et al.* 2018). As a result, it is very important to explore the dynamic deformation characteristics of EPS particles light weight soil.

Based on the laboratory test results, the empirical model of the backbone curve, the increase characteristics of damping ratio and the attenuation characteristics of dynamic shear modulus of EPS particles light weight soil are put forward (Gao *et al.* 2017). The damping of cement solidified substance, the damping of EPS particles and the "structural damping" of the contact surface between EPS particles and cement solidified substance are the main reasons for the increase of damping ratio. The dynamic shear modulus of EPS particles light weight soil is reduced because of the contact failure between the EPS particles and the cement solidified substance. The dynamic strength characteristics of EPS particles light weight clay is studied (Gao and Li 2007). It is found that the dynamic strength of light weight clay increases with the increase of cement content and confining pressure, but with the increase of cement content, the influence of confining pressure on dynamic strength of light weight clay weakens. The cement content and EPS particles mixed ratio have great influence on the dynamic cohesion of light weight soil and have no influence on the dynamic internal friction angle. The experimental results show that under the same dynamic stress, the greater the cement content and confining pressure is, the smaller the dynamic strain of light weight soil is (Li and Gao 2007; Li *et al.* 2008). Under the same dynamic strain, with the increase of cement content and confining pressure, the damping ratio decreases and the dynamic elastic modulus increases. There are less researches about the influence of EPS particle sizes on the mechanical properties of light weight soil. The

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shear strength of three kinds of light weight soil are studied by direct shear tests, and EPS particle sizes of three kinds of light weight soil are 2 ~ 3.5 mm, 3.5 ~ 5 mm, 5 ~ 6 mm, respectively. It is found that under the same cement content and EPS particles volume ratio, the shear strength of light weight soil decreases with the increase of EPS particle sizes, and the shear stress-shear displacement relationship of light weight soil is affected by normal stress and cement content (Hou and Xu 2011). There are strain softening and strain hardening for shear stress-shear displacement relationship curves, and it is suggested that 3 ~ 5 mm EPS particles should be used in the construction process. The unconfined compressive strength, structural strength, compressive modulus and swelling index of light weight soil with different spheroid, fragment and flake EPS particles are studied (Ma 2001). It is considered that light weight soil with 1 ~ 3 mm EPS beads or flake EPS particles whose density is about 1.0 g/cm^3 can meet the requirements of embankment fillings. The deformation characteristics of light weight soil with different EPS particle sizes are studied by consolidation tests, it is found that the lateral confined stress-strain curve is S-type curve (Hou 2012). When the cement content and EPS particles volume ratio are constant, the structural strength of light weight soil decreases with the increase of EPS particle sizes, but the compressibility indexes basically remain unchanged. It is found that EPS particle sizes has a certain influence on the shear strength, structural strength and deformation characteristics of light weight soil.

The macroscopic mechanical parameters of dynamic deformation of EPS particles light weight soil can be only obtained by general laboratory tests. It is difficult to find out the microscopic mechanism of soil particles in the process of shear tests and the particles movement law in the interior of sample is not analyzed, which limits the further study of dynamic deformation. With the rapid development of modern computer application technology, PFC^{3D} numerical simulation technology emerges as the times require, discrete element method can simulate the mechanical properties of granular material under indoor tests from the perspective of discontinuous media. A model that rock is represented by the dense accumulation of round or spherical particles of non-uniform size is put forward (Potyondy and Cundall 2004). These particles are bonded together at their contact points. Meso-parameters consist of stiffness and strength parameters of particles and bonds. It is considered that the failure of the bond is the fracture of the bond. When the load is applied, the fracture bond gradually appears and combines into macroscopic fracture. A double-concave bonding model is proposed, and the bonding effect between two particles in granular materials is simulated by discrete element method (Chiu *et al.* 2015). The model adopts a more realistic shape of cementation and considers the elastic response of cementation under external load. The results show that the model is effective for cemented granular materials under different compression conditions. In addition, the required parameters of this model can be obtained from the bonding properties of materials instead of the traditional inversion method.

PFC^{3D} numerical simulation technology is widely used to study the meso-mechanical properties of rock and soil. Based on the flexible particles film loading method, PFC^{3D} software is used to simulate the large triaxial tests of earth-rock mixture (Zhang *et al.* 2019a; Zhang *et al.* 2019b). It is found that with the increase of confining pressure, the ability of resistance to deformation and shear strength of numerical samples increase. With the increase of rock content, the cohesion decreases and the internal friction angle increases linearly. The failure form of the sample is bulging deformation. Due to the rotation and slip of the internal particles, a small crack is formed, many cracks are gradually connected through the sample and the shear zone is formed. The macroscopic and mesoscopic mechanical characteristics and deformation failure mechanism of earth-rock mixtures with different rock content are deeply analyzed (Jin and Zeng 2018a, 2018b; Jin *et al.* 2018). It is found that with the increase of rock content, the skeleton structure influence of earth-rock mixtures becomes more and more obvious, and the rotation quantities of soil particles in shear zone are larger than that of block stone particles, which indicated that the shear surface bypasses larger block stone particles. The rock cutting test is numerically simulated by discrete element method (Zhang *et al.* 2015). The special solid model built by Pro/ENGINEER5.0 is imported into PFC^{3D}, and then the rock cutting model is established. By simulating the unconfined compressive test and Brazil test, the macro parameters of the particle are corrected. The research shows that the number of cracks in tensile failure is about three times that in shear failure, so cracks formed under tensile failure condition are the main failure mode. The polyhedron particles are introduced to simulate the direct shear tests of sandy pebble soil, which overcome the limitation of spherical particles (Wu *et al.* 2014). It is found that the greater the contact stiffness of sand pebble is, the faster the shear stress rises and the higher the stress peak value is in direct shear tests. The macroscopic phenomenon of the sample gradually changes from shear contraction to the shear dilatation. By analyzing the sensitivity of macroscopic and mesoscopic parameters of gravel soil, it is found that there is a linear positive correlation relationship between cohesion and contact adhesion and particle friction coefficient. And the shear strength, residual strength and internal friction angle are nonlinearly positive correlated with particle friction coefficient (Dong *et al.* 2015; Ma *et al.* 2016).

PFC^{3D} numerical simulation technology can also be used to explore the meso-mechanical properties of geosynthetics. A bolt model based on discrete element software PFC is proposed, which uses high strength and high stiffness particle interface to simulate the interface between bolt and surrounding rock (Weng *et al.* 2020). The accuracy of the proposed model is verified by laboratory pull-out tests and shear tests. The finite element and discrete element methods are used to establish a coupling frame, and it is proposed that when the geogrid system is pulled from the particles material, the performance of geogrid system embedded in particles materials depends on the geogrid material, the properties of the backfill soil and the interface properties between geogrid and backfill soil (Tran *et al.* 2013, 2015). The interface characteristics of geogrid in direct shear tests are studied by discrete element method (Ngo *et al.* 2014). It is found that under the shear stress of 15 ~ 75 kPa, the locking influence of ballast fillings and geogrid is an important factor for the stability of geogrid. To sum up, the discrete element method is feasible to simulate the geotechnical tests. The PFC^{3D} software can be used to simulate the dynamic triaxial tests of EPS particles light weight soil and study the influence of particle sizes on its dynamic deformation characteristics.

Under the premise of cement mixed ratio of 15% and EPS particles volume ratio of 50%, indoor dynamic triaxial tests are carried out on three kinds of light weight soil with different EPS particle sizes of 1 ~ 3 mm, 3 ~ 5 mm, and 5 ~ 6 mm. The influence law of particle sizes on hysteretic curve of light weight soil is studied. However, only macroscopic mechanical parameters can be obtained by laboratory tests, and the stress state and movement law of the particles inside the sample is impossible to find out. So it is necessary to explore the change laws of mesoscopic parameters in light weight soil. The dynamic triaxial test of light weight soil is simulated by PFC^{3D} discrete element software. Taking the cohesion and cement cementation of light weight soil into account, the contact force distribution map and displacement field of the sample are analyzed. The mesoscopic mechanism of EPS particle sizes on the dynamic deformation characteristics of light weight soil is revealed from the particles level.

2. DYNAMIC TRIAXIAL TESTS OF LIGHT WEIGHT SOIL

2.1 Experimental Materials

The loess is taken from Yang Ling, Shaanxi Province, China, and its color is yellowish brown, which belongs to low liquid limit silty clay. Through standard compaction tests, the optimal moisture content is 20.51% and the maximum dry density is 1.69 g/cm^3, and the basic physical properties are shown in Table 1. EPS beads as light weight material produced by Ruitaida Energy Saving Technology Co., Ltd are used in the tests. The specific physical parameters are shown in Table 2. The solidified substance is PC32.5R composite Portland cement whose brand is Dunshi Jidong. Its pure particles density is 3.12 g/cm^3. Water is ordinary tap water.

Table 1 Basic physical properties of Yangling loess

Natural water content w (%)	Natural density ρ (g/cm^3)	Specific gravity G_s	Plastic limit w_p	Liquid limit w_L	Plasticity index I_P	Liquidity index I_L	Void ratio e
19.83	1.75	2.72	21.30	37.43	16.13	− 0.09	0.86

Table 2 Basic physical parameters of EPS particles

Shape	Particle size d (mm)	Pure particle density ρ_e (g/cm^3)	Bulk density ρ_v (g/cm^3)
Spherality	1 ~ 3	0.0318	0.2020
	3 ~ 5	0.0138	0.0087
	5 ~ 6	0.0094	0.0062

2.2 Sample Preparation and Test Scheme

Firstly, crush the raw soil into powders, dry it and pass it through a 2 mm sieve. Then mix loess and cement evenly according to the material mixed ratio. Next, add water to the cement-loess mixture and use the spatula to mix them fully until the mixture is homogeneous mud. Weigh the EPS particles with different particle sizes, add them into the mud body and stir them evenly. Using pouring method to fill light weight soil into the three-petal molds, whose diameter is 39.1 mm and height is 80.0 mm. In order to avoid the large pores in the sample, the samples should be compacted as much as possible. Label the samples and put them into the standard curing box for 24 hours, the temperature is 20±2°C and the humidity is greater than 95%. After removing the molds, the samples are cured until 28th day.

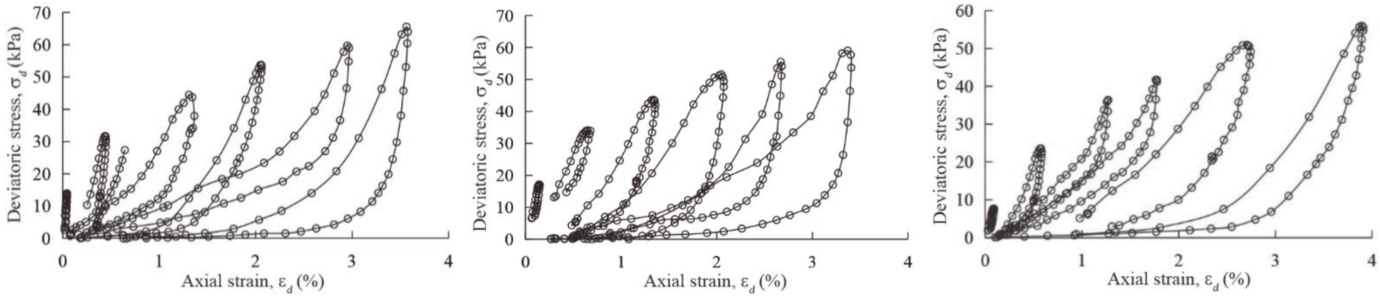
Xi'an Lichuang STD-20 type soil dynamic triaxial testing machine is used in the tests. The height of the sample is 80.0 mm, its diameter is 39.1 mm, and the specific test scheme is shown in Table 3. Taking the mass of dry soil m_s as the standard, the cement content is $a_c = m_c/m_s \times 100\%$, where m_c is the mass of cement. The moisture content is $w = m_w/m_s \times 100\%$, where m_w is the mass of water. EPS particles volume ratio is $b_e = v_e/v \times 100\%$, where v_e is EPS particles volume and v is the volume of the sample. First, the samples are vacuumed for 1 hour and saturated in the water for 24 hours. The consolidation stress ratio, $K_c = 1.0$, applies confining pressure to the specimens for drainage consolidation. Then close all the valves connected with the triaxial pressure chamber, carry out dynamic triaxial tests without water discharge. The sinusoidal wave cyclic load is applied, the dynamic shear stress ratio is 0.075. The stress-controlled graded loading is adopted, the vibration of each stage is 10 times, and the failure standard is 5% axial strain.

2.3 Test Results and Analysis

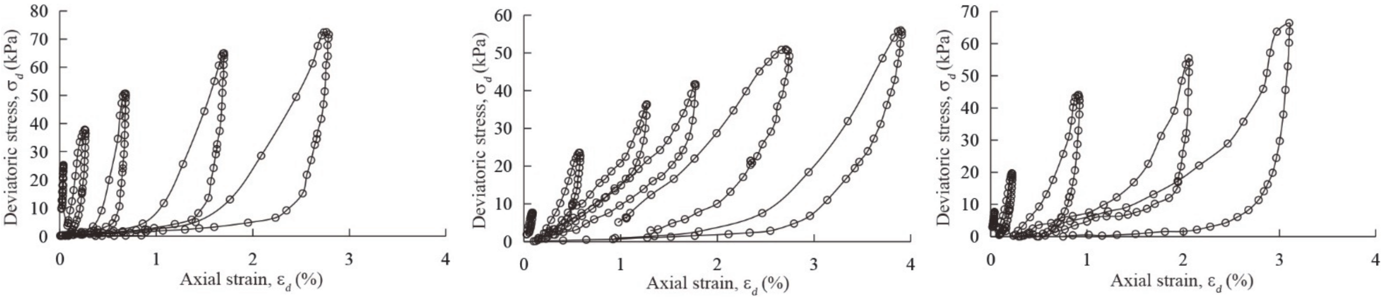
The hysteretic curve reflects the stress-strain relationship of the sample under dynamic load at every point in time and it is the fundamental embodiment of dynamic characteristics for soils. As shown in Fig.1: (1) There is only compressive stress curve without tensile stress curve in the hysteretic curve of light weight soil. Because the sample contains cement, it has strong resistance to deformation, and light weight soil shows a certain shear strength when compressed by the vibration shaft. The sample is stretched by the rubber film, the sample is separated from the vibration shaft, so the sample can not resist tensile stress. (2) The hysteretic curve reflects the hysteresis that dynamic strain lags behind dynamic stress in light weight soil. With the increase of load, the peak value of dynamic stress of hysteresis loop of each stage increases, the corresponding dynamic strain increases gradually, and the central point of the hysteresis loop moves towards the direction that dynamic strain increases, which indicates that light weight soil has strain hardening and strain accumulation characteristics. (3) When other conditions keep constant, the peak value of dynamic stress in each stage gradually decreases with the increase of EPS particle sizes. As shown in Fig. 1(c), 1(g), and 1(k), when the confining pressure is 150 kPa, the mixed ratio of light weight soil is $a_c = 15\%$, $b_e = 50\%$. Taking the dynamic strength of light weight soil whose EPS particle sizes is 1 ~ 3 mm as the standard, when the diameter of EPS particles increases from 1 ~ 3 mm to 3 ~ 5 mm and 5 ~ 6 mm, the dynamic strength of light weight soil decreases by 15.53 kPa and 33.27 kPa, respectively, and the relative attenuation rates of dynamic strength are 15.29% and 32.76%, respectively. (4) When other conditions keep constant, the peak value of dynamic stress in each stage increases with the increase of confining pressure. As shown in Fig.1(e), 1(f), 1(g), and 1(h), when the diameter of EPS particle sizes is 3 ~ 5 mm, the mixed ratio of light weight soil is $a_c = 15\%$, $b_e = 50\%$, taking dynamic strength of light weight soil under the confining pressure of 50 kPa as the standard. When the confining pressure increases from 50 kPa to 100 kPa, 150 kPa, and 200 kPa, the dynamic strength of light weight soil is 68.31 kPa, 86.03 kPa and 103.23 kPa, respectively. The absolute increasement of dynamic strength of light weight soil is 9.03 kPa, 29.02 kPa, and 44.22 kPa, respectively. The relative growth rate of dynamic strength of light weight soil is 15.76%, 49.18%, and 74.94%, respectively.

Table 3 Dynamic triaxial tests scheme of light weight soil

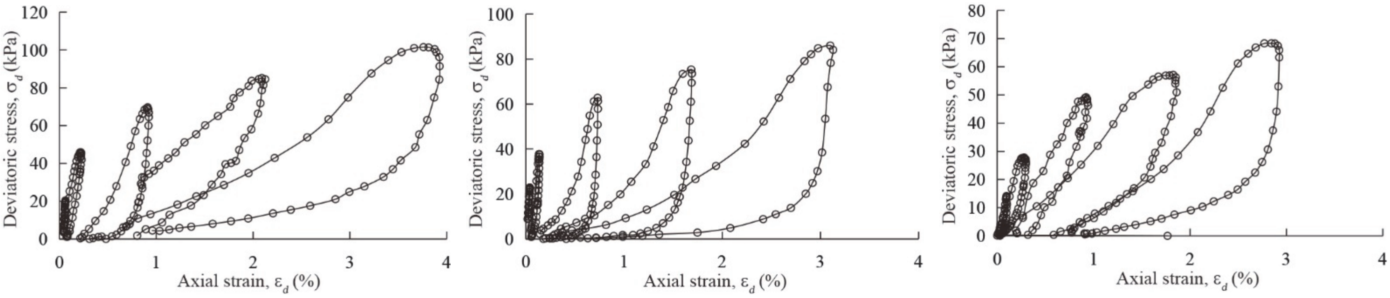
Cement mixed ratio a_c (%)	EPS particles volume ratio b_e (%)	EPS particle sizes D (mm)	Water content w (%)	Age T (day)	Confining pressure σ_c (kPa)	Frequency f (Hz)
15	50	1 ~ 3, 3 ~ 5, 5 ~ 6	50	28	50, 100, 150, 200	1



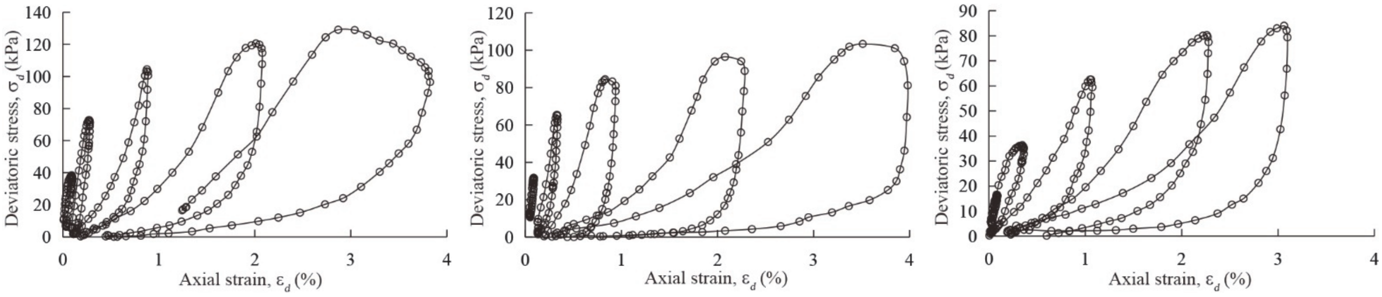
(a) d = 1 ~ 3 mm, σ_c = 50 kPa (e) d = 3 ~ 5 mm, σ_c = 50 kPa (i) d = 5 ~ 6 mm, σ_c = 50 kPa



(b) d = 1 ~ 3 mm, σ_c = 100 kPa (f) d = 3 ~ 5 mm, σ_c = 100 kPa (j) d = 5 ~ 6 mm, σ_c = 100 kPa



(c) d = 1 ~ 3 mm, σ_c = 150 kPa (g) d = 3 ~ 5 mm, σ_c = 150 kPa (k) d = 5 ~ 6 mm, σ_c = 150 kPa



(d) d = 1 ~ 3 mm, σ_c = 200 kPa (h) d = 3 ~ 5 mm, σ_c = 200 kPa (l) d = 5 ~ 6 mm, σ_c = 200 kPa

Fig. 1 Hysteresis curves of dynamic triaxial tests of EPS particles light weight soil (a_c = 15%, b_e = 50%)

The reason that affects the strength of light weight soil is cavity. Since cement and soil have hydrophilicity, EPS particles have hydrophobicity. After hydrolysis and hydration of cement, cement and soil form a unified structure, EPS particles as soft inclusion, have only a certain bonding influence. The strength of light weight soil mainly comes from the cohesion of soil and cement cementation, EPS particles mainly play a density-reduction role in the sample. When the cement mixed ratio and EPS particles volume ratio keep constant, the pure particles density decreases with the increase of EPS particle sizes, and a larger "cavity body" is produced in the sample. The weak contact surface between EPS particles and cementing substance increases and stress concentration is easy to occur, which leads to the decrease of the peak value stress of light weight soil under each stage dynamic stress and the decrease of dynamic strength. With the increase of confining pressure, the sample is in a denser state, the contact of each component is closer, the overall loading inside the sample increases, the peak value of dynamic stress also increases, and the dynamic strength of the sample increases.

3. NUMERICAL MODELING OF PARTICULATE DISCRETE ELEMENT METHOD

3.1 Mechanical Principles of Particulate Discrete Element

The particulate discrete element method takes rigid particles as the basic cell. By establishing the parametric model of solid particle system, the movement law and contact state of rigid particles are simulated, and the mechanical properties of materials are studied from a mesoscopic level. The contact type between EPS particles and soil particles is flexible contact; there is some overlap in the contact position; and the deformation of particles does not need to meet the deformation coordination condition.

3.2 Numerical Modeling

As shown in Fig. 2, the cylinder, upper and lower plane walls are established to simulate the triaxial chamber. The height of triaxial chamber is 80.0 mm, and its diameter is 39.1 mm. As shown in Fig. 3, EPS particles groups with different particle sizes and soil particles groups are randomly generated and they are filled in triaxial chamber. Yellow particles represent soil particles and gray particles represent EPS particles. Taking cohesion of loess and the cementation of a small amount of cement into account, contact bond between EPS particles and soil particles is set, and the normal and tangential bonding strength are expressed by n_b and s_b, respectively, where n_b is normal bonding strength and s_b is tangential bonding strength.

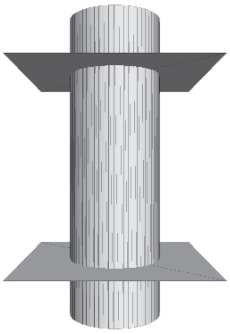
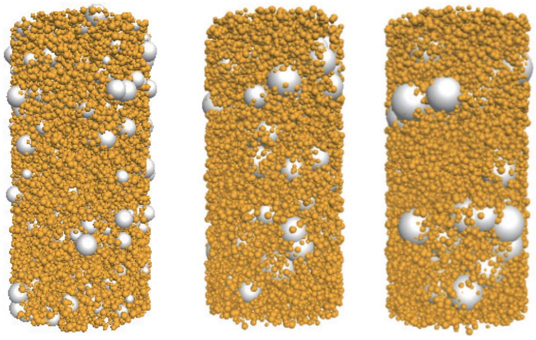


Fig. 2 Dynamic triaxial constraint environment



(a) $d = 1 \sim 3$ mm (b) $d = 3 \sim 5$ mm (c) $d = 5 \sim 6$ mm

Fig. 3 Numerical samples of EPS particles light weight soil with different particle sizes (n_b = s_b = 3 × 10^8 N/m, b_e = 50%)

During the calculation, the spherical particles displacement is used to simulate the movement of soil particles and EPS particles in the indoor dynamic triaxial tests. By using the servo mechanism to keep the confining pressure constant, the movement of the top and bottom loading plates of model are controlled to apply the axial load to the sample in the form of simple harmonic waves. The axial stress is obtained by dividing the contact force between particles and the top or bottom loading plate by the area of the loading plate, the axial strain is obtained by dividing the displacement difference between the top and bottom loading plates by the initial height of the sample, and the stress and strain values are recorded by using History command.

In order to make it possible that the hysteretic curve obtained by discrete element method can be compared with that of the indoor tests, the correct mesoscopic parameters should be selected, and mesoscopic parameters can be obtained by referencing some modeling experience (Ma *et al.* 2016; Jin *et al.* 2018; Jin and Zeng 2018; Wu *et al.* 2018). In terms of light weight soil, the normal stiffness k_n and tangential stiffness k_s have little influence on the macroscopic elastic modulus and the peak value of dynamic stress. 1/10 stiffness of top and bottom loading plates is taken as the stiffness of sidewall to simulate the flexible boundary of the rubber film. Friction coefficient μ between EPS particles and soil particles mainly influences the peak value of dynamic stress, and bond fracture during loading is influenced by the contact bonding strength between soil particles and EPS particles. By constantly adjusting PFC^{3D} mesoscopic parameters of the numerical model, the final mesoscopic parameters are shown in Table 4.

3.3 Analysis of Numerical Simulation Results

Under the confining pressure of 100 kPa, the hysteretic curves of indoor dynamic triaxial tests of samples with different EPS particle sizes are compared with that of discrete element method of samples, and the sixth circumference vertices of each stage hysteresis loops of discrete element method are marked as A-O points, respectively. It is found from Fig. 4 that the hysteretic curves of indoor tests and discrete element method have the same points: (1) The change laws of dynamic stress-dynamic strain relationship of discrete element method is similar to that of indoor tests, and the peak value of dynamic stress of discrete element method and the corresponding axial strain are almost the same as that of indoor tests. (2) Under the same amplitude, the peak values of dynamic stress of discrete element method and indoor tests decrease slightly with the increase of EPS particle sizes. It is found that the three-dimensional discrete element model can simulate the indoor dynamic triaxial tests of light weight soil well.

Table 4 Mesoscopic parameters of dynamic triaxial tests numerical model of light weight soil

Materials	Density (kg/m^3)	Friction coefficient	Normal stiffness (N/m)	Tangential stiffness (N/m)	Normal bonding strength (N/m)	Tangential bonding strength (N/m)
Soil particles	2,720	0.4	3.0×10^8	1.0×10^8	3.0×10^8	3.0×10^8
EPS particles	31.8	0.4	4.0×10^7	2.0×10^7		
	13.8	0.4	2.0×10^7	1.0×10^7		
	9.4	0.4	1.2×10^7	0.6×10^7		
Top and bottom loading plates	–	0.3	3.0×10^8	3.0×10^8	–	–
Sidewall	–	0.3	3.0×10^7	3.0×10^7		

But the hysteretic curves of indoor tests are different from that of discrete element method in the following three differences:

(1) The axial strains corresponding to the peak value of dynamic stress of indoor tests are different from that of discrete element method under the same amplitude. For example, when the EPS particle sizes are 1 ~ 3 mm, 3 ~ 5 mm, and 5 ~ 6 mm at the fifth stage load, the axial strains of samples of indoor tests are 2.78%, 2.89%, and 3.10%, respectively, but the axial strain of numerical samples does not show a significant increasing trend. Under the condition of constant cement content and EPS particles volume ratio in the indoor tests, with the increase of EPS particle sizes, the stiffness of samples decreases and the ability to resist deformation weakens. Under the same dynamic load, the larger EPS particle sizes is, the higher the axial strain is. The particles are rigid spheres in PFC^{3D} software, and the change of axial strain of sample is caused by particles displacement. The increase of EPS particle sizes causes the decrease of normal stiffness and tangential stiffness of EPS particles, and at the same time induces the change of contact area between EPS particles and soil particles. This may be the reason that the axial strain corresponding to the peak value of dynamic stress in numerical simulation does not show a significant increase trend.

(2) The hysteresis curve of discrete element method fluctuates greatly. This is because EPS particles account for 50% of the total volume in the sample and the particle sizes are larger than that of soil particles. During the loading process, the rotation and sliding of the particles update the relative position of the particles, leading to the change of contact state and the fluctuation of stress. With the increase of the EPS particles, the fluctuation is more obvious. Moreover, with the increase of EPS particle sizes, the stress fluctuation of sample is more obvious.

(3) In the unloading stage, the dynamic stress reduction path of the hysteretic curves of discrete element method is different from that of hysteretic curves of indoor tests for the samples. When the axial load changes from compressive stress to tensile stress in indoor tests, the sample has elastic deformation, the vibration shaft moves upward, the sample is gradually separated from the vibration shaft, and the dynamic stress of the sample decreases slowly. The reverse velocity is applied to the top and bottom loading plates to separate the sample from top and bottom loading plates in discrete element method, the contact force between top and bottom loading plates and sample, and dynamic stress of the sample decrease rapidly.

4. ANALYSIS OF MESOSCOPIC MECHANISM

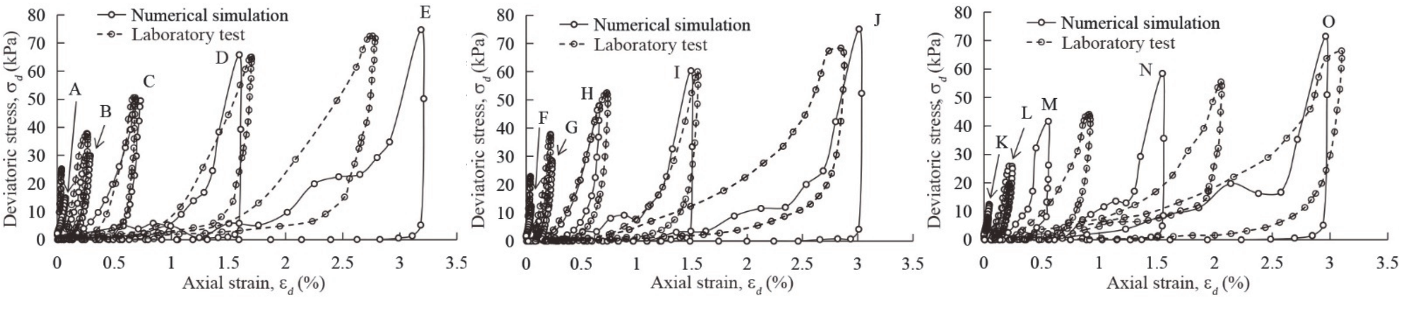
The shear failure of light weight soil is necessarily related to the stress state and particles displacement in the sample, due to the limitation of indoor tests, it is difficult to obtain mesoscopic data in the indoor tests. In order to explore the dynamic deformation characteristics of light weight soil, based on the numerical model of PFC^{3D} software, the influence mechanism of EPS particle sizes on the dynamic deformation of light weight soil is explained by the contact force distribution and displacement field in the vibration loading process.

4.1 Influence of EPS Particle sizes on Contact Force

Due to particles interaction in the sample, the contact force between the EPS particles and soil particles occurs in the loading process, which reflects the stress state in the sample. By analyzing the contact force distribution diagram of numerical samples under 100 kPa confining pressure, the influence laws of EPS particle sizes on the contact force between EPS particles and soil particles in light weight soil is explored. In order to present a clearer distribution of contact force, 5 mm cutting layer is cut by using slicing tool along the vertical direction in the middle of sample, and the size of the particles is reduced to 0.4 times of the initial particle sizes.

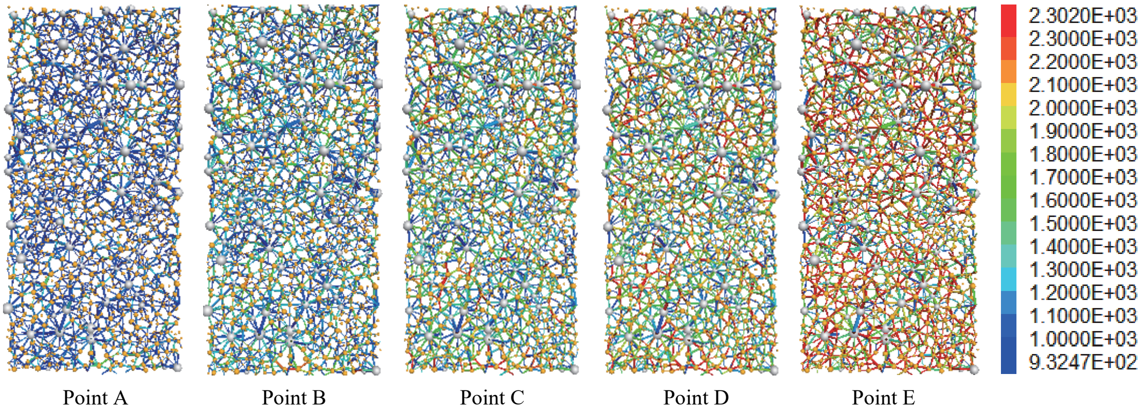
As shown in Fig. 5: (1) The change laws of contact force of numerical samples with different EPS particle sizes is basically the same. Taking numerical model of light weight soil with 3-5 mm EPS particles as an example, contact force between EPS particles and soil particles increases with the increasing load step by step from the time corresponding to point F to the time corresponding to point J. The normal contact force is equal to the product of the normal stiffness and overlap of the contact particles in PFC^{3D} software. Compared with the size of the particles, the value of the overlap can be neglected. The normal and tangential stiffness of EPS particles are smaller than that of soil particles, which makes it obvious that the contact force between EPS particles and soil particles is smaller than contact force between soil particles and soil particles.

(2) Under the condition of the same EPS particles volume ratio, the smaller the EPS particle sizes is, the more the number of EPS particles is, EPS particles are randomly distributed in the sample with a certain uniformity, and the distribution of contact force is relatively uniform. EPS is a light-weight high molecular polymer. The foaming agent is added into polystyrene resin, which is heated and softened at the same time to generate gas, thus forming a foam plastic with a hard closed-cell structure. The density of EPS

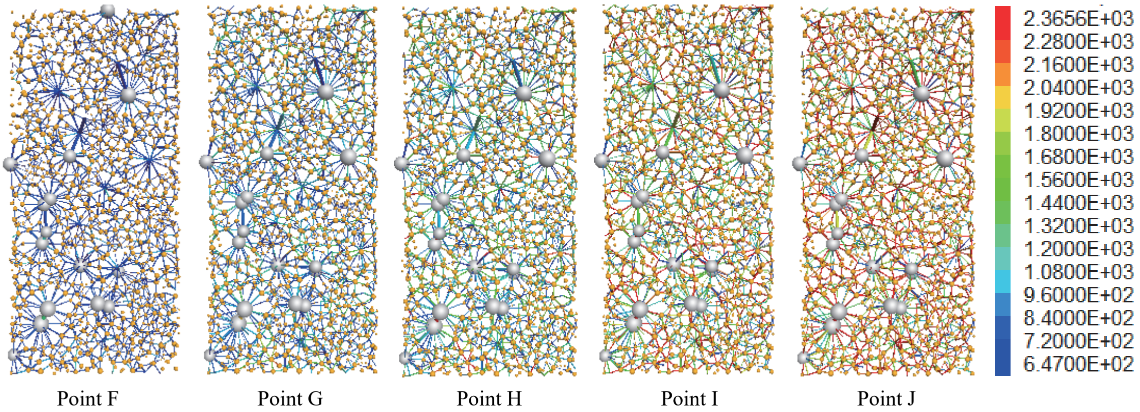


(a) d = 1 ~ 3 mm (b) d = 3 ~ 5 mm (c) d = 5 ~ 6 mm

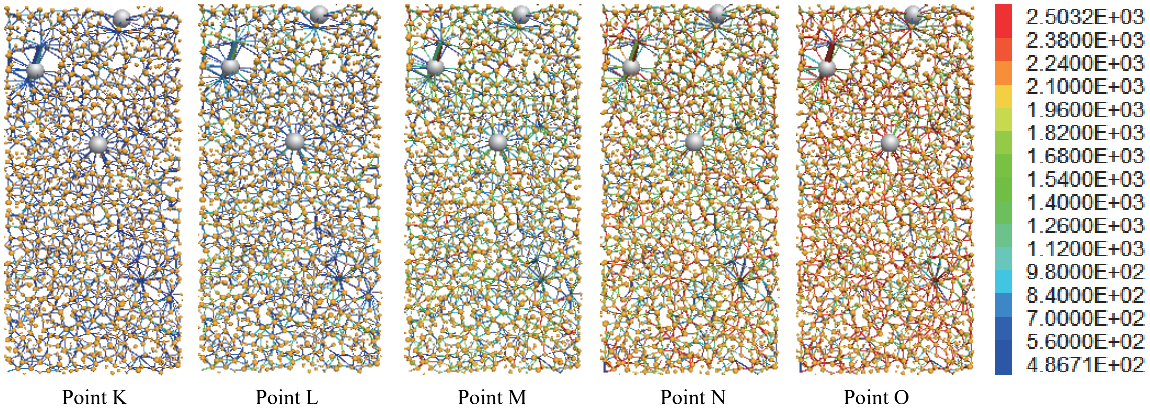
Fig. 4 Comparison of dynamic triaxial test hysteresis curves and numerical simulation results of light weight soil with different EPS particle sizes (a_c = 15%, b_c = 50%, σ_c = 100 kPa)



(a) $d = 1 \sim 3$ mm



(b) $d = 3 \sim 5$ mm



(c) $d = 5 \sim 6$ mm

Fig. 5 Contact force of dynamic triaxial test numerical samples of light weight soil (n_b = s_b = 3 × 10^8 N/m, b_e = 50%, σ_c = 100 kPa, the unit of contact force: N)

is determined by the expansion times of polystyrene particles in the forming stage. Density is an important index of EPS, and its mechanical properties are almost proportional to its density. The larger the EPS particle size, the smaller the pure particle density and accumulation density. With the increase of EPS particle sizes from 1 ~ 3 mm to 3 ~ 5 mm and 5 ~ 6 mm, the pure particle density decreases from 31.8 kg/m^3 to 13.8 kg/m^3 and 9.4 kg/m^3, the normal stiffness decreases from 4.0×10^7 N/m to 2.0×10^7 N/m and 1.2×10^7 N/m, the tangential stiffness also decreases.

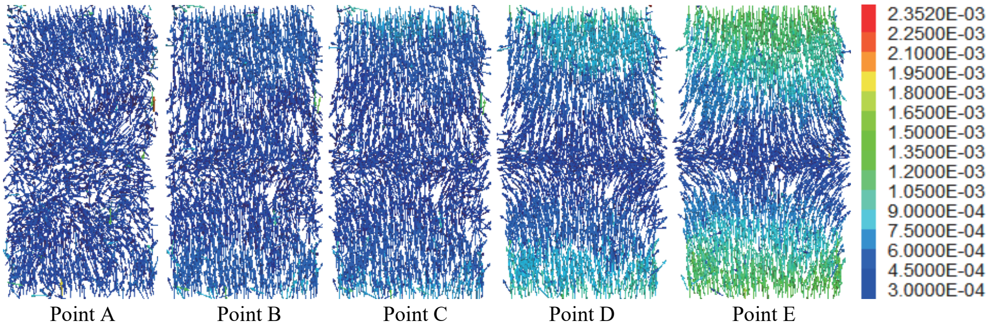
(3) The contact forces between EPS particles and EPS particles and EPS particles and soil particles decrease, the ability of EPS particles to resist loads is smaller, the soil particles skeleton system is subjected to larger loads, and the distribution of contact force between EPS particles and soil particles is more uneven. The whole stress state of the sample is changed, the stress concentration phenomenon occurs, and the specimen is more easily destroyed. And it is consistent with the laws that the dynamic strength of light weight soil decreases with the increase of EPS particle sizes.

4.2 Influence of EPS Particle Sizes on Displacement Field

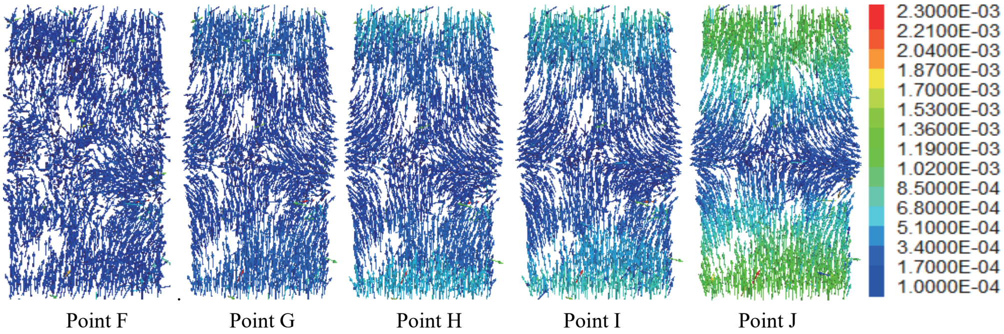
The stress in the sample transmits from some particles to other particles in the loading process, which makes the particles move and produce macroscopic mechanics and displacement response. By analyzing the displacement field of the numerical sample under 100 kPa confining pressure, the influence laws of EPS particle sizes on the particles movement in light weight soil are studied. The blank part in Fig.6 represents EPS particles.

As shown in Fig. 6: (1) The displacement field distribution law of light weight soil numerical samples with different EPS particle sizes is similar. Taking the numerical model of light weight soil with 3 ~ 5 mm EPS particle sizes as an example, the top and bottom particles in the sample move towards the middle of the sample from the time corresponding to point F to the time corresponding to point J, and the movement directions of particles gradually deflect, and the closer the particles is to the middle of the sample, the larger the angle of the particles deflection toward the periphery of the sample is. The displacement of the top and bottom particles in the sample is obviously larger than that of the particles in the middle of the sample, and the particles displacement overall increases with the increasing load step by step.

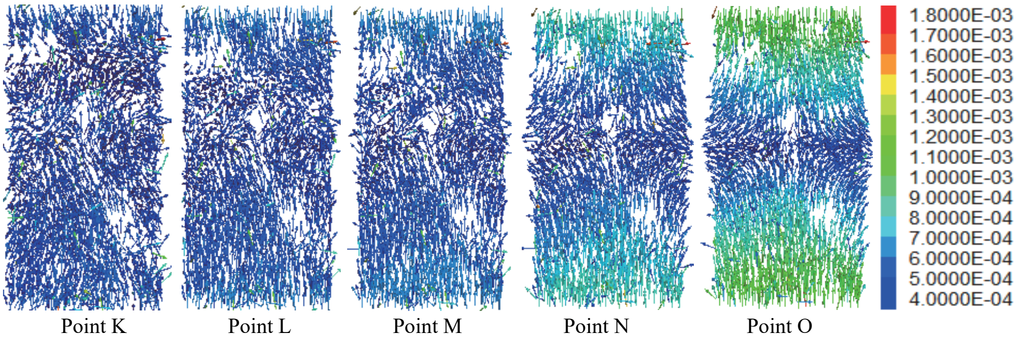
(2) The extrusion zone formed by the movement of particles from the top and bottom of the sample to the middle of the sample is called the "displacement interface". When EPS particle sizes are1 ~ 3 mm and 3 ~ 5 mm, respectively, the particles displacement of the sample is symmetrically distributed along the horizontal direction of the middle of the sample, and the displacement interface is always in the middle of the sample. When EPS particle sizes is 5 ~ 6 mm, the displacement interface is at the upper and middle of the sample in the initial stage of the loading. With the increase of dynamic load, the displacement field distribution gradually tends to distribute symmetrically along the horizontal direction of the middle of the sample, the displacement interface gradually moves from the upper and middle of the sample to the middle of the sample. When the EPS particles volume ratio is constant and the particles distribution is random, the particle sizes is inversely proportional to the number of EPS particles. The smaller EPS particle sizes is, the more uniform EPS particles distribution is, so the particles displacement distribution is symmetric under load with respect to the displacement interface. On the contrary, when the particle sizes is larger, the particles displacement field is asymmetric with respect to the displacement interface in the early loading period. But with the increasing of dynamic load step by step, the top and bottom particles displacement of the sample continuously increases, so the displacement interface moves gradually from the top and bottom of the sample to the middle of the sample. With the increase of EPS particle sizes, the arrangement state of particles in the sample changes, which affects the overall distribution of particles displacement and makes the extrusion zone move from top and bottom of the sample to the middle of the sample.



(a) *d* = 1 ~ 3 mm



(b) *d* = 3 ~ 5 mm



(c) *d* = 5 ~ 6 mm

Fig. 6 Displacement fields of dynamic triaxial test numerical samples of light weight soil (n_b = s_b = 3 × 10^8 N/m, b_e = 50%, σ_c = 100 kPa, the unit of contact force: m)

5. CONCLUSIONS

1. The hysteretic curves of light weight soil under dynamic load have the characteristics of strain hardening, hysteresis and strain accumulation. Under the condition of the constant cement content, EPS particles volume ratio and confining pressure, with the increase of EPS particle sizes from 1 ~ 3 mm to 3 ~ 5 mm and 5 ~ 6 mm, the contact area of the weak surface between EPS particles and solidified soil increases, which makes it easy that the stress concentration phenomenon occurs. The dynamic strength of light weight soil decreases by 4.17 ~ 25.88 kPa and 7.06 ~ 45.14 kPa with the increasing of EPS particle sizes from 1 ~ 3 mm to 3 ~ 5 mm and 5 ~ 6 mm, respectively. The relative attenuation rate of dynamic strength is 5.75% ~ 20.04% and 7.06% ~ 34.96% with the increasing of EPS particle sizes from 1 ~ 3 mm to 3 ~ 5 mm and 5 ~ 6 mm, respectively.
2. With the increasing load step by step, the contact force between EPS particles and soil particles result in overall increases, and the contact force between EPS particles and soil particles is always smaller than that between soil particles and soil particles. With the increase of EPS particle sizes, the normal and tangential stiffness decrease, which makes the contact force between EPS particles and soil particles smaller. The greater load the soil skeleton system bear, the more uneven the distribution of contact force is in the numerical sample. Stress concentration phenomenon occurs and the sample is more vulnerable to be damaged, and it is consistent with the law that the dynamic strength of light weight soil decreases with the increase of EPS particle sizes.
3. The particles at the top and bottom of the sample move towards the middle of the sample, and the displacement direction of particles gradually deflects. The closer the particles are to the middle of the sample, the larger the deflection angle toward the periphery of the sample. The displacement of top and bottom particles of the sample is always larger than that of the middle of the sample. With the increase of EPS particle sizes, the particles displacement distribution is asymmetric. But as the load increase step by step, the particles displacement at the top and bottom of the sample continuously increases, and the displacement interface moves gradually from the top and bottom of the sample to the middle of the sample, which makes the extrusion zone move from the top and bottom of the sample to the middle of the sample.

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DATA AVAILABILITY

The data and computer codes used in this study are available from the corresponding author on reasonable request.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

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