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# Dynamic characteristics of expanded polystyrene composite soil under traffic loadings considering initial consolidation state

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ABSTRACT

As a type of artificial filling material, the shear modulus and damping ratio of expanded polystyrene (EPS) composite soil are two key parameters used to analyze the dynamic stability of an embankment. Nineteen combined axial–torsional tests are conducted on hollow cylinder specimens of EPS composite soil to study its dynamic characteristics under the complex stress path induced by the simulated traffic loadings. The characteristics of skeleton curve, dynamic shear modulus and damping ratio for EPS composite soil are analyzed. It is found that EPS composite soil is characterized by typical dynamic nonlinearity, which is influenced by the mixing ratio and the initial stress state. The increasing cement content can effectively improve the dynamic strength of EPS composite soil. EPS bead content has a slight influence on the initial shear modulus of EPS composite soil as well as the cyclic stress-strain curve in the linear elastic stage. However, the increasing EPS bead content obviously reduces the dynamic strength. The initial shear modulus increases with increasing initial minor principal stress for the isotropic and anisotropic consolidated specimens. The characteristics of modulus attenuation are significantly influenced by the initial minor principal stress, EPS bead content and initial rotation angle of the major principal stress axis. The “structural damping” effect induced by the weak interface formed between EPS beads and cemented soil is an important component of the damping mechanism for the EPS composite soil. Based on the experimental results, this paper provides the empirical models to describe the skeleton curve, modulus attenuation and damping growth characteristics for EPS composite soil.

## 1. Introduction

Thanks to the rapid development of geotechnical materials and the requirements regarding the protection of the environment since the middle of the past century, a new type of filling material—namely, EPS composite soil—is proposed and utilized in practice in the 1960s. EPS composite soil is a mixture that is usually mixed with EPS (expanded polystyrene) beads, soil, cement and water. EPS composite soil has been widely used in many fields such as soft soil treatment, embankments and bridge abutments, expressways, and underground pipelines [1–6]. As a type of artificial geotechnical material, EPS composite soil is characterized by controllable strength and deformation, and its mechanical properties can be adjusted by changing the mixing ratio to satisfy the requirement [7–9]. In addition, it is a type of environmentally friendly material [5,8]. For instance, some wastes such as dredged mud and waste packaging foam can be used to prepare EPS composite soil. In terms of convenience of construction, EPS composite soil possesses high fluidity and good workability, which can meet the requirement of uniformity and compactness as a bulk mass filling material.

Over the past twenty years, numerous tests have been conducted on EPS composite soil to study its physical and mechanical characteristics. Conventional testing methods are adopted, including unconfined compression tests, uniaxial compression tests, direct shear tests, and triaxial compression tests [10–12]. The mixing ratio and its influence on the strength, deformation and failure modes have been investigated and discussed [13–15].

When used on land, in the coast, or underwater, EPS composite soil is likely to undertake cyclic loadings such as seismic loading, traffic loading, or wave loading. Therefore, the dynamic characteristics of EPS composite soil are also a concern for engineering. At present, the dynamic characteristic studies on EPS composite soil are focused on the cyclic stress–strain relationship, modulus, damping ratio, dynamic strength and so on. Some factors affecting dynamic characteristics are discussed such as the mixing ratio, initial loading condition (the magnitude and frequency of cyclic loading, initial consolidation condition) and curing days. The conventional resonance column test and cyclic triaxial shear test are the most commonly used methods.

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When used as the filling material of an embankment, EPS composite soil is in a complex stress state, which can be reflected in the followings: 1) the initial stress conditions differ for the soil at different positions; not only is the initial consolidation stress ratio different but also the principal stress axis rotates more obviously for the soil close to the slope shoulder; and 2) under the traffic loadings, the principal stress axis in the soil continuously rotates and the stress path displays a typical 'heart' shape. In fact, the existing studies on sand, soft soil or mixed soil have shown that the influence of the rotation of the principal stress axis on the strength and deformation of soils cannot be neglected [16–18].

The cyclic torsional shear test on hollow cylinder specimen is the most effective approach to study dynamic behavior of soil under complex stress conditions [19,20]. The hollow cylinder torsional apparatus can independently apply the axial force, torque, inner and outer confining pressure to the specimen, which makes it possible to simulate the complex initial stress condition and multiple loading stress paths. The torsional shear tests on the hollow specimens have been employed to study cyclic behavior of sandy and clayey soils under drained or undrained condition, including cyclic shear strength (liquefaction resistance) and residual deformation and so on [21–24]. In the meantime, it is widely used to evaluate the dynamic performance of soil under cyclic loading conditions such as traffic loading, seismic loading, or wave loading [25,26]. However, the present studies have not paid sufficient attention to the influence of the initial stress condition and complex stress path induced by traffic loadings on the dynamic characteristics of EPS composite soil.

In this paper, a series of combined axial–torsional tests on EPS composite soil were conducted to investigate its dynamic characteristics under different initial stress conditions and a 'heart-shaped' stress path. The characteristics of the cyclic stress–strain relationship, shear modulus and damping ratio for EPS composite soil are discussed, considering the change of cement content, EPS bead content and curing days. The influences of initial stress state parameters including the initial mean effective principal stress, consolidation stress ratio, intermediate principal stress coefficient and rotation angle of the principal stress axis are discussed in detail.

## 2. Experimental program

### 2.1. Material properties

The EPS composite soil used in this paper is a type of manmade mixture that is mixed with soil, EPS beads, Portland cement and water. The soil sample is muddy and silty clay and taken from Yangzi Jiang River belonging to floodplain phase deposits. The physical and mechanical properties of the muddy and silty clay are summarized in Table 1.

The EPS beads shown in Fig. 1 are produced from expandable polystyrene resin, which contains microscopic cells filled with a blowing agent (usually pentanes or butanes). The resin is exposed to steam under controlled pressure, which softens the cell walls. The beads are formed after the blowing agent expands and causes individual resin beads to increase in volume by up to 40 times. The particle size of the round EPS beads ranges from 2 to 3 mm. The bulk unit weight of EPS beads is 0.159 kN/m$^3$. Portland cement (P.O 32.5) is used as a binding material and water is used to carry out the hydration reaction and facilitate the mixing process.

**Fig. 1.** EPS beads used in the study.

### 2.2. Specimen preparation

The specimen preparation process for EPS composite soil is as follows: 1) the soil is oven-dried and then crushed into powder with a rubber hammer; 2) according to the desired mixing ratio, the dried soil and Portland cement are weighed and mixed; 3) the desired water is added into the mixture and stirred for approximately 10 min until uniform slurry is formed; 4) the desired amount of EPS beads are added into the slurry and fully stirred again for approximately 10 min until a uniform mixture is formed; and 5) the mixture is placed into a sampling device and cured for the required number of days.

The hollow cylinder specimen of EPS composite soil in this study is 60 mm in inner diameter, 100 mm in outer diameter and 200 mm in height. To prepare and cure the specimen, a sampling device is independently developed in Nanjing Tech University, China. The sampling device mainly comprises a three-section inner mould, three-section outer mould, top plate and base, as shown in Fig. 2. After the prepared mixture is placed into the sampling device, a small amount of water is apt to accumulate at the bottom. The accumulated water is drained by the drainage slot designed at the bottom shown in Fig. 2(d) to avoid its influence on the specimen formed during the curing process.

Generally, the specimen can be released from the sampling device after curing for 24 h. The demolding process was separated into three steps as follows: 1) the smaller part of the inner mould was pulled out by a steel hook passing through a hole in it, and then the other two larger parts were removed as shown in Fig. 2(a); 2) the outer mould with the hollow cylinder specimen was placed on the top plate, and then the specimen was slowly pushed down by pressing the porous plate onto it as shown in Figs. 2(b) and (c); and 3) the specimen for EPS composite soil was obtained as shown in Fig. 2(d). After demolding, the specimen was cured inside the curing box with a constant temperature of 20 ± 2 °C and relative humidity at 100% until the testing date. Compared with the conventional sampling method, the approach proposed herein can reduce the disturbance to the hollow specimen during the demolding process to ensure the integrity of the specimen.

### 2.3. Testing program and loading method

#### 2.3.1. Testing program

The purpose of this paper is to discuss dynamic characteristics of EPS composite soil under complex stress conditions. Two factors affecting the dynamic characteristic of EPS composite soil are discussed: the mixing ratio and initial stress condition. Regarding the mixing ratio,

**Table 1**
Physical and mechanical properties of the muddy and silty clay.

| Water content $w$ (%) | Natural unit weight $\gamma$ (kN/m$^3$) | Saturation degree $S_a$ (%) | Void ratio $e$ | Specific gravity $d_s$ | Liquid limit $w_L$ (%) | Plastic limit $w_p$ (%) | Compression coefficient $a_{1\text{-}2}$ (MPa$^{-1}$) | Modulus of compressibility $E_s$ (MPa) |
|---|---|---|---|---|---|---|---|---|
| 48.1 | 16.8 | 96.0 | 1.37 | 2.74 | 39.2 | 22.6 | 0.98 | 2.42 |