

# A NOVEL METHOD FOR DETERMINING SOIL DAMPING RATIO COMBINING DMA AND STRAIN ENERGY

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**ABSTRACT:** Despite extensive research efforts, no comprehensive method for measuring soil damping has been established at either the national or international levels. In this study, a novel approach is introduced, utilizing a box-soil structure combined with Dynamic Mechanical Analysis (DMA) to experimentally determine the damping loss factor for both the box-soil structure and an empty box. Simultaneously, finite element analysis was employed to calculate the strain energy of the soil and the box separately. This process allowed for the derivation of the damping value in soil, presenting an innovative and accessible method for assessing soil damping. Additionally, this research offers a systematic approach to investigating soil damping patterns and compares the results with conventional triaxial dynamic testing. The comparison affirmed the viability of this new technique. The results show that the damping loss factor of soil increases and then decreases with the strain, with the maximum value. By calculation, the damping ratio of soil is between 0.08 and 0.3, and the damping ratio ( $\lambda$ ) increases as dynamic shear strain ( $\gamma$ ) increases and its range and change trend are consistent with the results obtained by conventional test methods.

*Keywords: Damping ratio, Damping loss factor, Silty clay, Box-soil structure, Dynamic mechanical analysis*

## 1. INTRODUCTION

The engineering characteristics of geotechnical bodies have consistently posed significant challenges in the realm of geotechnical engineering. Due to the complex composition of geotechnical media, the relationship between stress and strain is intricate and influenced by numerous factors. Although extensive research has been conducted both domestically and internationally in recent years, resulting in notable advancements in theory and numerical simulation methods, these developments are still insufficient to meet the evolving demands of geotechnical engineering. There are two primary reasons for this inadequacy: first, the uncertainty associated with geotechnical mathematical models, and second, the uncertainty of geotechnical body parameters. It's evident that the challenges posed by inaccurate mathematical models and imprecise input parameters have become the bottlenecks in delving deeper into the properties of geotechnical media and addressing real-world engineering issues.

Soil damping ratio is a pivotal parameter in soil dynamics, essential for seismic response analysis of soil layers and vital for the anti-vibration design in civil engineering structures. The appropriateness of the chosen soil damping ratio directly influences the safety and economic feasibility of engineering building structures [1,2]. However, as of now, no systematic and reliable method has been established, either domestically or internationally, to measure soil damping. Therefore, research into the soil

damping ratio is not only an extension of our understanding of the fundamental properties of geotechnical bodies but also holds profound significance for addressing the myriad geotechnical issues arising from deep underground space development and seismic challenges impacting building structures.

For indoor research on soil dynamic characteristics, the most widely used instrument, both domestically and internationally, is the dynamic triaxial apparatus [3-7]. Most dynamic modulus-damping tests are conducted following the recommended procedures in the Soil Test Operation Procedure, which involves consolidating 4-6 samples and subjecting each to vibrations under 3-5 different dynamic stresses for 2-3 weeks. The stress-strain relationship is then recorded using an oscilloscope, illustrating the soil as a viscoelastic body and calculating dynamic moduli and damping ratios from it. The results of the dynamic triaxial test usually have the axial dynamic strain [8,9] (or dynamic shear strain,  $\gamma$ ) on the x-axis and dynamic modulus  $E_d$  (or  $G_d$ ) and damping ratio  $\lambda$  on the y-axis, from which the maximum dynamic modulus  $E_{dmax}$  (or  $G_{dmax}$ ) and damping ratio  $\lambda_{max}$  are determined. However, the process of testing and data analysis is tedious, the test results often show considerable scatter, and their accuracy and reliability are low [10,11]. Moreover, with some soils, detachment of the sample from the vibrating axis is common in regular dynamic triaxial tests, making it difficult to obtain consistent dynamic

modulus and damping values [12,13].

Although dynamic triaxial tests and resonant column tests are widely used for a variety of soils, including sand, clay, and gravelly soils [14,15], these methods have inherent limitations due to their specific focus areas. Dynamic triaxial tests are primarily concerned with low-frequency (0.1 Hz-1 Hz) large to medium strains (>0.1%), while resonant column tests emphasize high-frequency (10 Hz and above) low strains (<0.1%). These distinct focus areas prevent them from fully capturing the broad range of dynamic soil behavior that occurs under varying loading conditions. In particular, in complex field environments, soils may experience dynamic loads spanning a wide range of frequencies and strains, making it difficult for these methods to provide a comprehensive understanding of soil behavior. Addressing these limitations and developing more comprehensive methods or hybrid techniques could significantly enhance the understanding and predictive capability of soil behavior under dynamic loading conditions.

Dynamic Mechanical Analysis (DMA), as an emerging testing technology, can accurately measure parameters such as the storage modulus, loss modulus, and damping factor of materials at small strain amplitudes. This offers a non-destructive, high-precision method for testing the dynamic properties of materials, opening new possibilities for in-depth studies on the damping performance of soil. Particularly in studying the dynamic properties of complex soils like expansive soil, DMA technology, with its high sensitivity and broad testing frequency range, can reveal the detailed dynamic response characteristics of materials under different conditions. The introduction of DMA technology has paved a new way for in-depth studies on the damping performance of expansive soil. In recent years, DMA technology, as an effective method for testing the mechanical properties of materials, has been widely used in the study of the mechanical properties of polymers, composite materials, and soils, among others [16-18].

Consequently, this study proposes a novel method for testing soil damping values, aiming to effectively address the limitations inherent in dynamic triaxial testing. Utilising a plastic box-soil structure, this research establishes a new rapid, simple, and indirect method to determine soil damping. The concept involves experimental testing of the damping loss factor of both the box-soil structure and the empty box using the DMA, followed by computational estimation of the strain energy of the soil and the box using finite element software. This allows for the derivation of the soil's damping loss factor, which can be converted to obtain the damping ratio of soil, presenting a novel and convenient method to test soil damping and a systematic approach to experimentally study the

patterns of soil damping.

## 2. RESEARCH SIGNIFICANCE

This study introduces a novel method combining a box-soil structure with Dynamic Mechanical Analysis (DMA) to experimentally assess the damping loss factor of both the box-soil structure and the empty box. Finite element software was employed to compute the strain energy of the soil and the box independently. A dynamic model for root-reinforced clay soil was proposed to elucidate the mechanism by which root systems improve the dynamic properties of clay soil. The study presents a systematic experimental approach for investigating soil damping patterns and compares these findings with conventional triaxial dynamic testing.

## 3. ENERGY DISSIPATION RELATIONSHIP OF COMPOSITE STRUCTURES

In composite materials, the method of modal strain energy to study the damping properties of composite materials has matured. For instance, Bai et al. [19] employed the strain energy method to investigate the damping characteristics of composite cylindrical tubes, formulating the corresponding dynamic equations. Yan et al. [20] utilized the ANSYS modal strain energy method to determine the modal structure loss factor. Alavinezhad et al.[21] conducted numerical studies on the damage of composite structures based on modal strain energy and implemented experimental modal analysis on it. Pan et al. [22] integrated the modal superposition method with the modal strain energy method, deriving a computation method for the loss factor of viscoelastic damping structures under arbitrary harmonic excitations. The modal strain energy method, throughout the research process combined with experimental data and software simulation, fully leveraged the computational advantages of software. The outcomes indicated that the software computation results not only conformed well with the experimental test results but also aligned closely with existing theoretical analysis results[22]. This method effectively addressed the problem of calculating the damping loss factor of composite materials.

Drawing from the research approaches mentioned above, for the composite box-soil structure made up of one elastic material (box) and another viscoelastic material (soil), in line with the energy dissipation conservation relationship for structures and neglecting the frictional loss at the contact surface between the box and the soil, the damping loss factor of the box-soil structure can be represented as:

$$\beta = (\beta_f W_f + \beta_v W_v) / W_s \quad (1)$$

In Eq. (1),

$\beta$  represents the loss factor of the box-soil composite structure.

$\beta_f$  denotes the damping loss factor of the empty plastic box.

$\beta_v$  signifies the damping loss factor of the soil packed inside the box.

$W_s$  is the total strain energy of the composite structure.

$W_f$  is the strain energy of the empty plastic box.

$W_v$  is the strain energy of the soil packed inside the box.

$W_s, W_f, W_v$  can be obtained through computations in the ANSYS software, while  $\beta_v, \beta$  can be derived from tests using the DMA instrument. With the parameters mentioned above, the damping loss factor of the soil can be deduced.

#### 4. DAMPING LOSS FACTOR AND DAMPING RATIO

The method of DMA single cantilever structure to test the damping performance of the sample is a very effective and simple method. However, DMA instrument does not directly test the damping ratio of the sample, but tests the loss tangent angle  $\tan \delta$  of the sample, that is, the phase difference between displacement and load. But in soil mechanics, soil is an elastic-plastic nonlinear body, and its damping condition does not strictly conform to the above ideal assumption. For elastic-plastic nonlinear energy dissipation like soil, the energy dissipation is often equivalent to linear damping.

Modulus is the stress-strain ratio of a material under stress, which is expressed as the overall resistance of the material to deformation. Corresponding to different stress states, there are different names, for example, elastic modulus, shear modulus, volume modulus, compression modulus, etc. In DMA-Q800 test, we use modulus to characterize the viscoelastic characteristics of materials under dynamic load. In materials engineering, the loss factor is used to characterize the damping parameters of viscoelastic materials. The loss factor is also called the tangent of the loss angle [23], and they can be represented by the following relationship:

$$\tan \delta = \eta = E'' / E' \quad (2)$$

Where,

$E''$  is the loss modulus, representing the viscous nature of the material, that is, the ability to dissipate energy.

$E'$  is the storage modulus, representing the elasticity of the material, that is, the ability to store energy.

The relationship among  $\delta, E''$  and  $E'$  is illustrated in Fig.1.

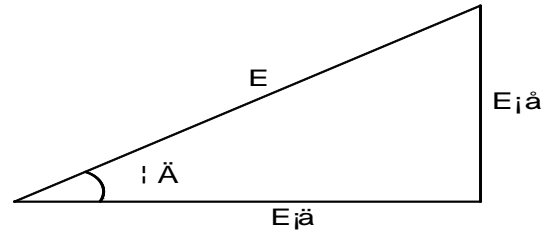


Fig. 1 The vector diagram

The damping ratio ( $\lambda$ ) is defined as the ratio of the damping coefficient ( $c$ ) to the critical damping coefficient ( $c_{cr}$ ). As determined through dynamic triaxial testing on soil, this damping ratio represents the energy dissipated in each vibration cycle of a sample. It is also commonly referred to as the soil's equivalent viscous damping ratio.

The damping ratio  $\lambda$  obtained from the dynamic triaxial test for soil can be represented as:

$$\lambda = A / 4\pi A_s \quad (3)$$

In Eq.(3),  $A$  and  $A_s$  respectively represent the area of the hysteresis loop ABCDA and the area of triangle OAE in Fig. 2.

Therefore, the relationship between the damping ratio and the loss tangent can be expressed as detailed in [24]:

$$\lambda = A / 4\pi A_s = 2\pi E'' / 4\pi E' = \tan \delta / 2 \quad (4)$$

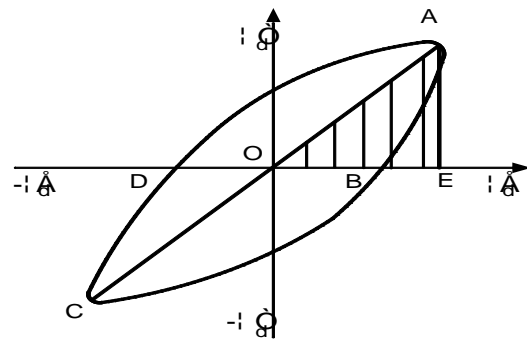


Fig. 2 Hysteretic loop of stress-strain of viscous-elastic

## 5. EXPERIMENTAL MATERIALS AND METHODS

### 5.1 Experimental Materials

The test box is made of transparent polypropylene (PP) plastic. The external dimensions of the box are 40mm×15mm×5mm. Other parameters are presented in Table 1. In this study,

powdery clay was selected as the test soil due to its typical representativeness in many geotechnical engineering applications.

Table 1. The Basic parameters of the box and soil

Name	E(Pa)	$\nu$	Density(kg/m <sup>3</sup> )
Soil	2.50E+07	0.35	1450
Box	1.32E+09	0.4	900

The soil used for disturbance tests comes from the powdery clay region of Shaoguan, Guangdong. It has a moisture content of 23.91% and a dry density of 1.61. In its loose state, the soil has a density of 1450kg/m<sup>3</sup>. Determining the elastic modulus and Poisson's ratio of the soil is relatively complex. For the sake of simplicity, data from the literature [20] was used. During instrument testing, the powdery clay was packed into the box and compressed, achieving a post-compaction density of 1775kg/m<sup>3</sup>, as illustrated in Fig. 3.



Fig. 3 Sample image of box-soil

### 5.2 Test Methods

The DMA (Dynamic Mechanical Analysis) instrument is commonly used to test the damping factor of materials such as plastics and rubbers. It is commonly employed in dynamic mechanical testing to primarily determine the relationship between temperature, time, frequency, stress, strain, dynamic modulus, and loss parameters of materials under specific controlled conditions. Samples tested on this instrument must be solid and mouldable. However, soil, being a granular material, is challenging to mould. Even if the soil sample is consolidated into a shape, it may still disperse under dynamic loads due to its weak cohesion.

To facilitate the DMA testing of soil samples, we developed a plastic box in which the soil sample is compacted. The compacted soil sample and the box are then tested as a single entity on the instrument. This approach allows us to measure the damping parameters of the soil-box combination without contaminating the instrument. Viewing the soil-box combination as a composite material, and using Eq. (1) and Eq. (4) in conjunction with experimentally measured damping loss factor data and strain energy

data calculated from ANSYS, we can derive the damping ratio of the taken soil sample.

To better simulate the actual stress conditions of the specimen, a comparative study of the double-cantilever and single-cantilever testing modes was conducted, considering the limitations of the test setup. Both testing modes subject the specimens to shear force, bending moment, and axial force, which closely resemble the stress states of soil in real-world conditions. However, under the double-cantilever condition, the stiffness of the box is relatively high, which diminishes the apparent interaction of the soil within the box.

Therefore, the experimental instrument was DMA-Q800 manufactured by TA. The test adopts a single cantilever mode, with specimen dimensions of 40mm × 15mm × 5mm (length × width × height). One end of the sample is fixed on the fixture, and the load is applied in the middle, and the sample is forced after the force. The instrument tests the storage modulus and loss modulus of the sample, and the ratio of the two is the damping loss factor. The instrument uses a strain scanning mode with a fixed frequency. The amplitude varies from small to large, with the temperature maintained at room level. The amplitude range for testing is between 0.1μm and 1000μm (The corresponding strain changes ranged from 1E-5 to 1E-2.). Several amplitudes within this range are selected for testing. A schematic of the testing setup is shown in Fig 4.

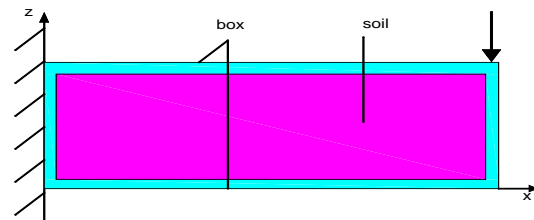


Fig. 4 Schematic diagram of single cantilever beam testing using of DMA

### 5.3 Calculation of Strain Energy

ANSYS finite element software was employed for modelling the actual structure, using the SOLID45 element for simulation. The boundary conditions were set such that one end was fixed while a harmonic displacement load was applied to the opposite end. It was assumed that during the testing process, the box-soil structure behaves as a linear elastic body. The contact surfaces between the two components perfectly overlap, with no local misalignment or relative movement. Consequently, during the software simulation, the box and soil are treated as a singular entity. The nodes on the contact

surface of both materials fully coincide. Only material non-linearity is considered, excluding geometric non-linearity and any misalignment issues at the interface between the two mediums. This ensures that the deformation between the box and soil at the contact surface is coordinated. The elemental model is illustrated in Fig.5.

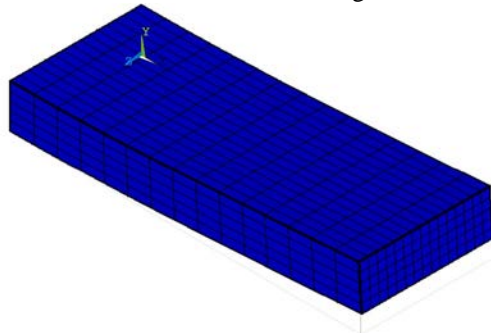


Fig. 5 ANSYS modeling graphic

## 6. RESULTS AND DISCUSSION

Initially, the empty plastic box specimens were tested using the Dynamic Mechanical Analysis (DMA) instrument at a fixed frequency of 0.1 Hz, conducting amplitude scanning to obtain the damping loss factor of the empty box, as shown in Fig.6. Subsequently, the soil was filled into the box and compacted, with its density being recorded. The same instrument was then used to test under the same conditions to obtain the damping loss factor of the soil-box composite structure, as shown in Fig. 7. Finally, the corresponding strain energy was calculated using the ANSYS software. Based on Eq.(1) and Eq.(4), the damping ratio of the soil can be computed.

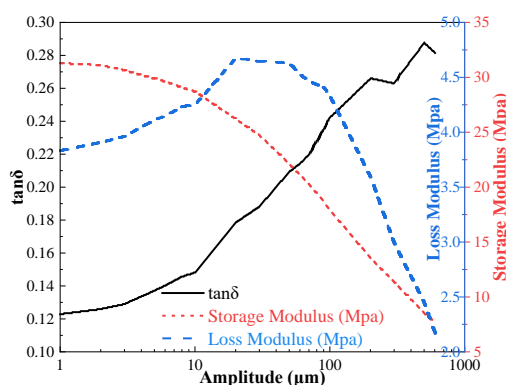


Fig. 6 Damping loss factor of the empty box via DMA testing

Fig.6 and Fig.7 illustrate the relationships between the damping loss factor, storage modulus, elastic modulus, and strain in the empty box and box-soil structures. As shown in the figures, the loss factor increases initially with strain and then

decreases, reaching a maximum value. Meanwhile, the storage modulus and loss modulus of expansive soil decrease with increasing shear strain.

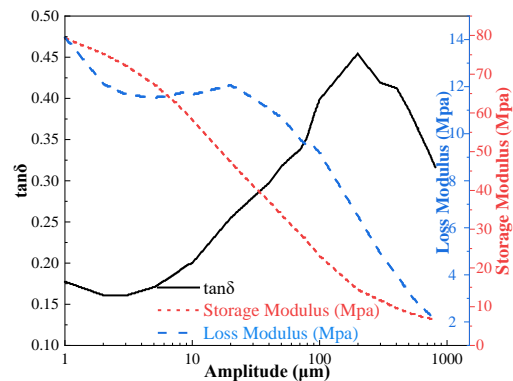


Fig. 7 Damping loss factor of the box-soil via DMA testing

To verify the feasibility of the experiment, the variation of soil damping parameters was calculated through five repeated tests, as shown in Fig.8. The damping ratio  $\lambda$  of the soil ranges between 0.08 and 0.3. Moreover, this range aligns with the results acquired from conventional testing methodologies. Furthermore, the trend showcasing an increase in  $\lambda$  with a rise in  $\gamma$  is also consistent with the patterns observed in traditional testing procedures. The new method can more accurately consider the environmental conditions of the sample and the influence of the force, and can record the change of damping parameters through continuous strain changes, to some extent avoid the uncertainty caused by a single input and output.

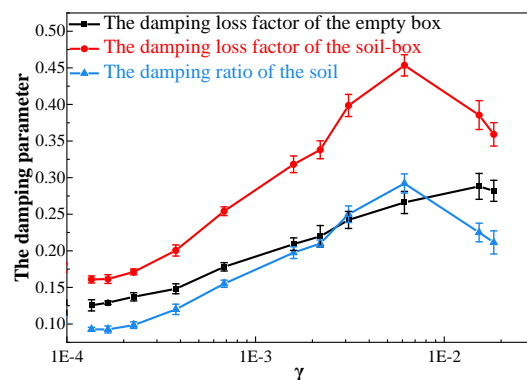


Fig. 8 Variation in damping parameters of empty box soil and box-soil

Domestic and international research on soil damping properties under laboratory conditions predominantly utilize Resonant Column Apparatus and Dynamic Triaxial Apparatus. Up until now, clear patterns have remained elusive. Generally, it's observed that as the amplitude of strain increases,

the damping ratio rises with the shear strain. When the strain amplitude is low, the curve is steep. After a certain strain amplitude, the curve gradually levels off, and the damping ratio tends to stabilize at its peak value, known as the maximum damping ratio [25-27]. For silty clay, the variations in damping ratio with changes in strain can be intricate. The relationship between damping ratio and dynamic strain is relatively scattered, with various sources offering differing conclusions[28-31]. Regardless of whether it's Resonant Column testing or Dynamic Triaxial testing, literature suggests that the damping ratio for silty clay generally lies between 0.05 and 0.3[29,31-35].

Given the significant difference in testing principles between the method used in this paper and traditional methods, and potential questions surrounding the precision of traditional test data, achieving results within the same range as traditional methods would validate the feasibility of this new approach. As indicated by Fig.8, the damping ratio parameters derived from the method employed in this study fall within the range established by traditional testing methods. To further align these results with conventional test outcomes, this paper utilizes damping data for silty clay from the study of Cai and Jin[33] for comparison. As illustrated in Fig.9, the dynamic shear strain ranges from  $1E-4$  to  $1E-3$ , and the damping ratio fluctuates between 0.08 and 0.2. The alignment between the damping ratios from the two different methods further substantiates the viability of this new technique. This confirms its precision within a specific range for measuring the damping ratio of silty clay, holding significant implications for future systematic investigations into how various parameters influence the damping ratio of soil.

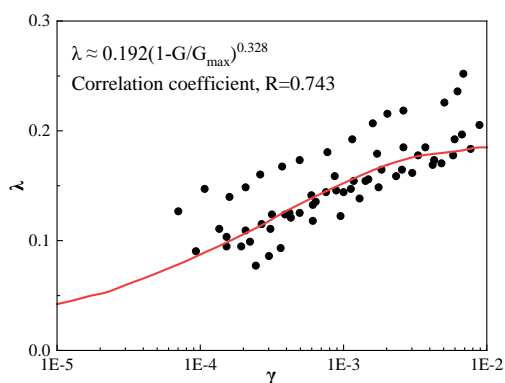


Fig. 9 Damping ratio values from referenced literature[32]

Nevertheless, when the shear strain approaches  $5E-3$ , a noticeable inflection point emerges on the damping ratio curve. As the shear strain exceeds  $5E-3$ , the damping ratio intriguingly diminishes, showing a clear discrepancy when compared to

results from Dynamic Triaxial testing. Potential reasons for this deviation are analyzed below:

(1) Differing Testing Methodologies:

The principles behind the two testing methods are distinct. In Dynamic Triaxial tests, cylindrical samples are used and are subjected solely to compressive forces. In contrast, the new method employs rectangular samples that, during instrument testing, experience both shear forces and bending moments. Under the influence of these shear forces and bending moments, the specimen is more prone to cracking and damage. When the shear strain exceeds  $5E-3$ —indicative of a high amplitude—it can be observed that the box is greatly deformed, and the contact force between the soil and the box will lead to smaller cracks in the internal soil. Consequently, as the damping ratio of the box-soil sample peaks, it then diminishes with increasing shear strain. The fact that the empty box doesn't exhibit a drop in its damping value at this juncture underscores that this reduction is likely due to damage inflicted on the soil at this specific shear strain.

(2) Potential Relative Slippage:

When the amplitude becomes excessively large, there might be a relative slippage occurring between the soil and the box. This is another plausible explanation for the observed peak in the box-soil damping ratio followed by its subsequent decline.

As we all know, in the process of earthquake, the frequency of earthquake is a range, including low frequency and high frequency. The damping ratio frequency of moving triaxial test and resonant column test soil is below 20Hz, while DMA instrument is as high as 200Hz. The DMA test can simulate changes in the performance of samples under different frequencies, offering a broader testing range. This method can be combined with the analysis of soil behavior under seismic conditions, providing valuable insights. In addition, the fixture tested by DMA instrument adopts single and double cantilever, and the sample is subjected to shear force, bending moment and axial force, while the soil sample tested by dynamic triaxial instrument is only subjected to axial force and shear force. In contrast, DMA can test the damping parameters of soil, which makes up for the shortcomings of dynamic triaxial instrument and other instruments.

## 7. CONCLUSIONS

This paper presents an innovative approach that involves constructing a unique box-soil structure and employing Dynamic Mechanical Analysis (DMA) for testing soil damping values. Additionally, finite element software was utilized to calculate the strain energy within the soil and box in the box-soil structure. This method not only offers a novel means of measuring soil damping but also demonstrates

greater accuracy and convenience compared to conventional techniques.

(1) The damping loss factor of the box-soil structure initially increases with shear strain and then decreases, reaching a maximum value. Additionally, the energy storage modulus and loss modulus both decrease as shear strain increases.

(2) When the shear strain ( $\gamma$ ) ranges from  $1E-5$  to  $1E-2$ , the damping ratio of the experimental sample soil varies between 0.08 and 0.3. This range aligns closely with results obtained from traditional testing methods, and the observed trend of the damping loss factor ( $\lambda$ ) increasing with  $\gamma$  is consistent with established patterns from conventional approaches. These findings demonstrate the effectiveness and feasibility of this new method.

Furthermore, this method facilitates field sampling, allowing for a more accurate consideration of the environmental conditions of the sample. By recording changes in damping parameters across a continuous range of strain, this approach reduces uncertainties associated with single-input and single-output tests, thereby ensuring that the test outcomes are more reliable and precise.

## 8. ACKNOWLEDGMENTS

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