

Research on nonlinear rheology perspective of loess mudflows based on large amplitude oscillatory shear (LAOS)

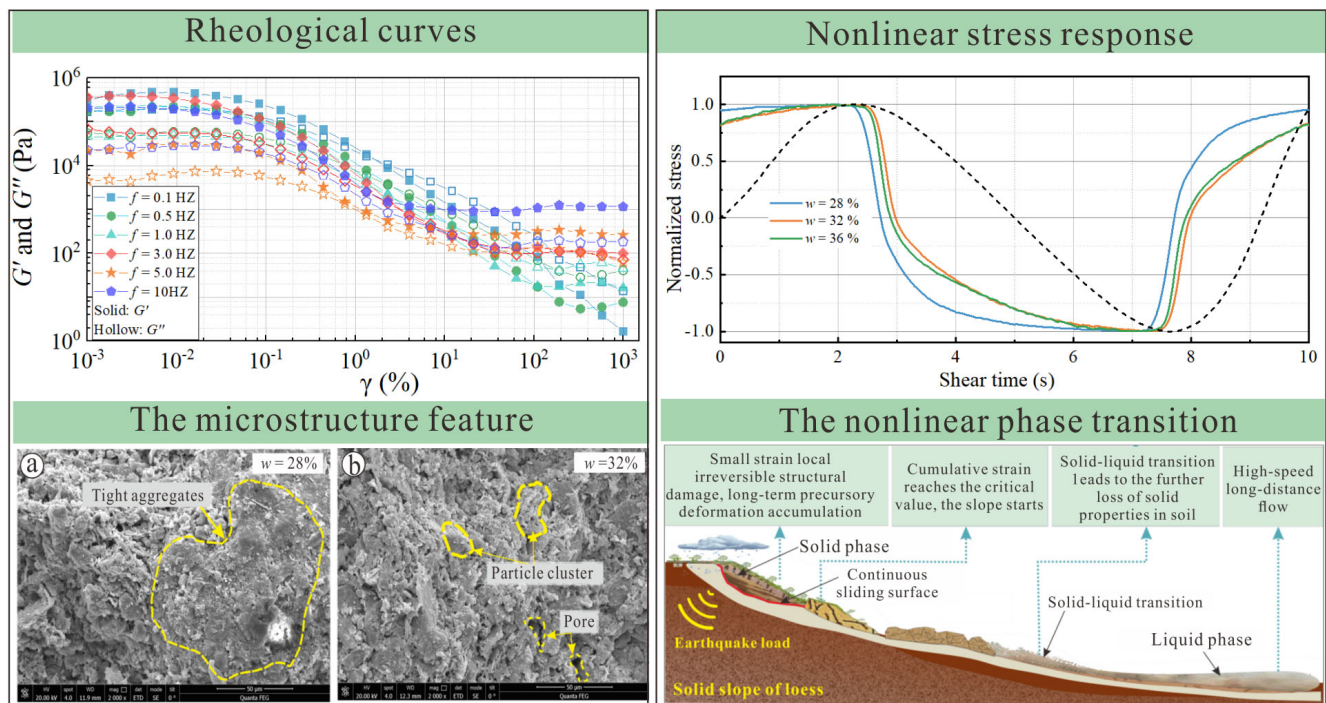
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Graphical Abstract



Highlights:

- LAOS and Fourier transform rheology define four characteristic strains that resolve the solid-fluid transition of loess mudflows.
- Water content and loading frequency jointly control the strain thresholds that characterize the solid-liquid transition of loess mudflows.
- The identified characteristic strains provide a strain-resolved basis for assessing yielding and supporting early warning of loess mudflow hazards.

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Abstract: Loess mudflows are typical geological hazards that undergo a dynamic solid-to-liquid transition, yet the yielding process remains poorly constrained. This study investigates the nonlinear rheological behavior of loess slurries with water contents of 28%, 32%, and 36% using large amplitude oscillatory shear (LAOS) and Fourier-transform rheology at frequencies from 0.1 to 10 Hz. Results show that the rheological response evolves from linear behavior to solid-like nonlinearity with a G'' overshoot, and finally to fluid-like behavior. Increasing frequency lowers the linear limit and nonlinear transition strain but raises the nonlinear limit and solid-liquid transition strain. Higher water content can increase the strain required for complete liquefaction; at 36% water content and 5–10 Hz, G' remains above G'' and no solid-liquid transition occurs. The nonlinear coefficient Q remains nearly constant at small strains and decays with increasing strain and sensitive to strain, water content, and frequency, serving as an early indicator of structural change. SEM observations reveal that higher water content disperses the soil structure and weakens interparticle interactions, explaining the weaker nonlinearity and delayed fluidization. These findings provide a strain-resolved characterization of the solid-liquid transition in loess mudflows and offer theoretical support for hazard assessment and early warning.

Keywords: loess mudflow; nonlinear rheology; large amplitude oscillatory shear; fourier transform rheology; phase transition dynamics

1. Introduction

Many geological materials, such as volcanic ash, snow, clay, mud, and lava, often exhibit a dynamic solid to liquid transition during geophysical events (Peng *et al.* 2018; Lube *et al.* 2020; Breard *et al.* 2020, 2023; Jones *et al.* 2024; Coussot, 2025; Verdurme *et al.* 2025; Zuccarello *et al.* 2025). For instance, landslides and snow avalanches can evolve into debris flows during movement (Hung *et al.* 2014; Lei *et al.* 2025; Vicente *et al.* 2026). During earthquakes and heavy rainfall, volcanic ash and clay can suddenly fluidize and migrate from source areas over long distances (Kameda *et al.* 2019; Fan *et al.* 2025). Loess mudflows, as a common geological hazard in the Loess Plateau, also exhibit this characteristic of solid-liquid dynamic transition (Ma *et al.* 2022). The transition from a static state to a flowing state (solid-liquid phase transition) is the core dynamic problem governing the initiation, movement, and deposition of loess mudflows (Zhang *et al.* 2022; Wang

et al. 2025a, b). Therefore, a deep understanding of the solid-liquid phase transition dynamics of loess mudflows is of great significance for establishing scientific disaster prediction models and developing effective mitigation measures. Recent studies increasingly describe landslide and avalanche initiation as the outcome of coupled thermal, hydrological, topographic, and mechanical controls, while multi-parameter seismic metrics provide improved means of detecting and classifying rapid mass movements (Wang *et al.* 2026a, b). These event scale frameworks demonstrate the importance of resolving both triggering conditions and observable dynamic signatures.

To reveal the phase transformation dynamics of loess mudflows, the key lies in accurately describing its flow and deformation behavior under complex stress conditions. Rheology, as a science that studies material flow and deformation, provides an effective means for quantitatively characterizing the mechanical response of the slurry during its transition from solid to liquid state (Sumita *et al.* 2008; Wang *et al.* 2024; Coussot, 2025). For a long time, the rheological behavior of soil has mainly been

studied based on traditional steady-state shear tests and the Buckingham model or its modified forms (Herschel-Bulkley model) (Breard *et al.* 2024; Pradeep *et al.* 2024; Kamali Zarch *et al.* 2025). These models simplify the slurry as a fluid with a single yield stress, assuming that when the applied stress exceeds this threshold, the soil will instantly transform from solid to liquid state (Major *et al.* 1992; Jeong *et al.* 2015; Hu *et al.* 2022; Coussot, 2025).

This binary yield model offers a clear physical picture and simple parameters, and has been widely applied in engineering practice (Mainsant *et al.* 2012; Carrière *et al.* 2018; Vo *et al.* 2020). However, an increasing number of studies indicate that the phase transition of yield stress fluids is not a simple instantaneous jump (Coussot *et al.* 2002; Donley *et al.* 2019). Conventional steady state testing methods can only capture the average response of the soil, failing to capture the evolution of transient structures and energy dissipation mechanisms during the phase transition (Donley *et al.* 2020), nor can they reveal the precursory deformation characteristics prior to mudflow initiation.

Linear viscoelastic theory is of great significance for understanding the relationship between the microstructure and rheological properties of complex fluids, but this theory is strictly valid only when the total deformation is very small (Hyun *et al.* 2011). Complex fluids with similar linear viscoelasticity may exhibit significantly different nonlinear viscoelastic characteristics (Hyun *et al.* 2002; Donley *et al.* 2020). For instance, during actual mudflow movement, the soil often undergoes large deformation, high-rate shear, and a range of complex motions beyond the linear viscoelastic regime (Wang *et al.* 2025a, 2026c). In such cases, relying solely on linear viscoelastic characterization is insufficient to explain the actual rheological behavior under nonlinear conditions. In recent years, the development of nonlinear rheology has provided new theoretical tools and experimental methods for studying the phase transition behavior of complex fluids (Hyun *et al.* 2002). Among these, large amplitude oscillatory shear (LAOS) can simultaneously probe the elastic and viscous responses of test materials over a wide range of strains and frequencies, and is considered an effective means for studying the nonlinear behavior of yield stress fluids (Ewoldt *et al.* 2008, 2010; Kamani *et al.* 2021). Fourier transform rheology, by decomposing the stress response into harmonic components at multiple integer multiples of the fundamental frequency, can quantify the degree of nonlinearity and reveal the internal microstructural evolution of materials (Wilhelm *et al.* 2002; Hyun *et al.* 2011).

Previous rheological studies of loess mudflows have mainly examined the effects of water content and particle-size distribution using steady-state shear parameters or small-amplitude measurements (Huang *et al.* 2009; Holthusen *et al.* 2020; Cui *et al.* 2025; Wang *et al.* 2025a, 2026c). Although these studies established the basic dependence of rheological properties on material composition, steady-state parameters represent an

averaged response and cannot resolve the progressive structural rearrangement, harmonic distortion, and changing energy-dissipation mechanisms that occur during yielding. As a natural geological material with complex microstructure (wide particle size distribution, containing clay particles and a loose structure) (Derbyshire, 2001; Xu *et al.* 2012; Peng *et al.* 2018), the nonlinear rheological behavior of loess mudflow shares commonalities with synthetic soft materials, but also has its own unique features. The nonlinear response under oscillatory loading remains insufficiently characterized, particularly with respect to the coupled effects of water content and loading frequency.

This study investigated different moisture contents of loess slurry. Using LAOS tests combined with Fourier transform rheology, the effects of water content and frequency on the nonlinear rheological behavior of loess slurry were analyzed. By analyzing the storage modulus, loss modulus, high-order harmonic intensity, nonlinear characteristic coefficient Q , and viscoelastic characteristic parameters (linear viscoelastic critical strain, nonlinear transition point, nonlinear limit point, and solid-liquid transition point), the nonlinear characteristics and energy dissipation mechanism during the phase transition process were revealed. On this basis, combined with scanning electron microscopy (SEM) microstructural analysis, the microscopic physical mechanisms underlying the effects of water content and frequency on the nonlinear behavior are discussed. This study provides theoretical support for the initiation mechanism, solid-liquid transition characterization, and early warning of loess mudflow geohazards.

2. Theory

2.1. LAOS rheology

Loess mudflows are yield stress materials that may undergo large deformation and high rate shear during initiation and movement. Conventional steady state shear tests and small amplitude oscillatory shear mainly characterize the linear viscoelastic regime and therefore cannot fully resolve the structural damage and nonlinear energy dissipation that occur at large strains (Hyun *et al.* 2002, 2011; Donley *et al.* 2020; Costanzo *et al.* 2024).

Large amplitude oscillatory shear, or LAOS, extends the strain amplitude beyond the linear range and simultaneously probes the elastic and viscous responses of complex fluids (Ewoldt *et al.* 2008, 2010; Kamani *et al.* 2021). A sinusoidal strain with a prescribed amplitude and frequency is applied to the sample, and the resulting stress response is recorded. At small strain amplitudes, G' and G'' are approximately independent of strain and the response is linear viscoelastic. At larger amplitudes, the stress waveform becomes distorted, while the strain dependence of G' and G'' reflects progressive structural rearrangement (Atalik *et al.* 2004). Fourier transform rheology and stress decomposition methods can further

distinguish harmonic distortion and recoverable or unrecoverable deformation during yielding (Cho *et al.*

2005; Rogers *et al.* 2011, 2012). The representative linear and nonlinear LAOS responses are shown in Figure 1.

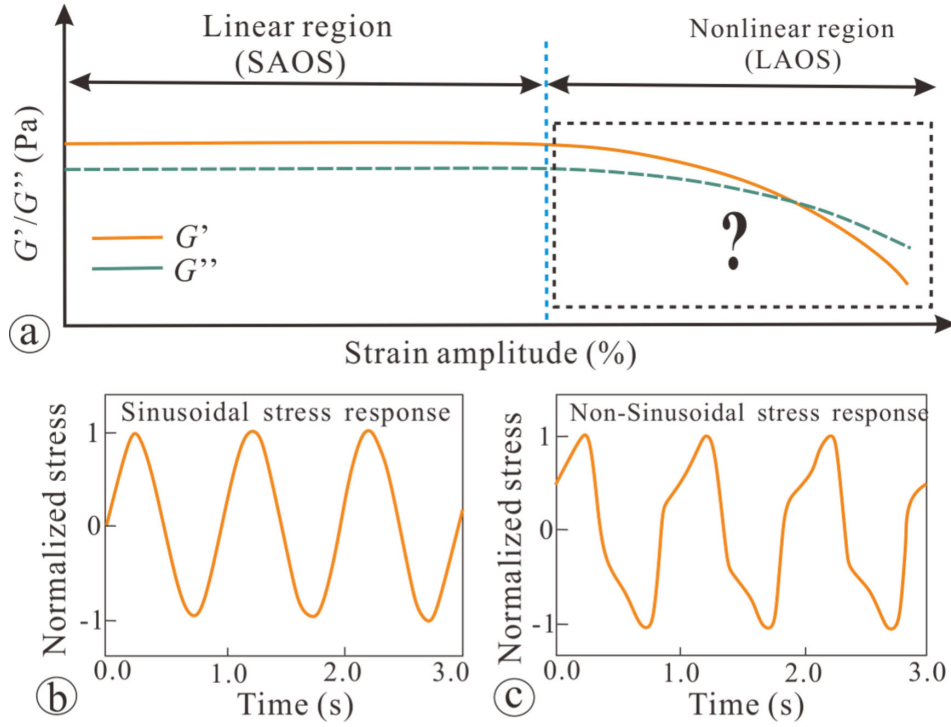


Figure 1. Schematic responses in large-amplitude oscillatory shear (LAOS). **(a)** Typical dynamic strain sweep test results; **(b)** Time-domain stress response under linear viscoelastic conditions; **(c)** Time-domain stress response under nonlinear viscoelastic conditions.

2.2. Fourier rheology

Fourier transform rheology represents the periodic stress response as a sum of harmonics of the imposed frequency (Wilhelm *et al.* 2002). The imposed strain and strain rate are given by Equations (1) and (2), and the linear stress response is described by Equation (3).

$$\gamma(t) = \gamma_0 \sin(\omega t) \quad (1)$$

$$\dot{\gamma}(t) = \gamma_0 \omega \cos(\omega t) \quad (2)$$

$$\sigma(t) = \sigma_0 \sin(\omega t + \delta) \quad (3)$$

where γ_0 is the amplitude of the sinusoidal shear strain waveform, ω is the oscillation frequency, and t is time, σ_0 is the amplitude of the output sinusoidal stress, and δ is the phase angle of the output sinusoidal stress.

When the material enters the nonlinear regime, higher harmonics appear and the stress response can be expressed by Equation (4).

$$\sigma(t) = \sum_{n=1}^{\infty} \sigma_n(\omega, \gamma) \sin(n\omega t + \delta_n(\omega, \gamma)) \quad (4)$$

Where n is the harmonic order, I_n and δ_n represent the harmonic intensity and phase angle of the n th harmonic, respectively.

For isotropic materials under sinusoidal shear, the dominant response is composed of odd harmonics, leading to Equations (5) and (6). The corresponding Fourier spectra are illustrated in Figure 2.

$$\sigma(t) = \sum_{\substack{n=1 \\ \text{odd}}}^{\infty} \sigma_n(\omega, \gamma) \sin(n\omega t + \delta_n(\omega, \gamma)) \quad (5)$$

$$\begin{aligned} \sigma(t) &= \gamma_0 \sum_{\substack{n=1 \\ \text{odd}}}^{\infty} [G_n^*(\omega, \gamma_0) \sin(n\omega t) + G_n^*(\omega, \gamma_0) \cos(n\omega t)] \\ &= \dot{\gamma}_0 \sum_{\substack{n=1 \\ \text{odd}}}^{\infty} [\eta_n^*(\omega, \gamma_0) \sin(n\omega t) + \eta_n^*(\omega, \gamma_0) \cos(n\omega t)] \quad n = 1, 3, 5.. \end{aligned} \quad (6)$$

Where G_n^* and G_n^* are the n the order nonlinear elastic modulus and viscous modulus obtained from Fourier transform, $\dot{\gamma}_0$ is the strain rate, and η_n^* and η_n^* represent the order dynamic viscosity and the anisotropic viscosity, respectively.

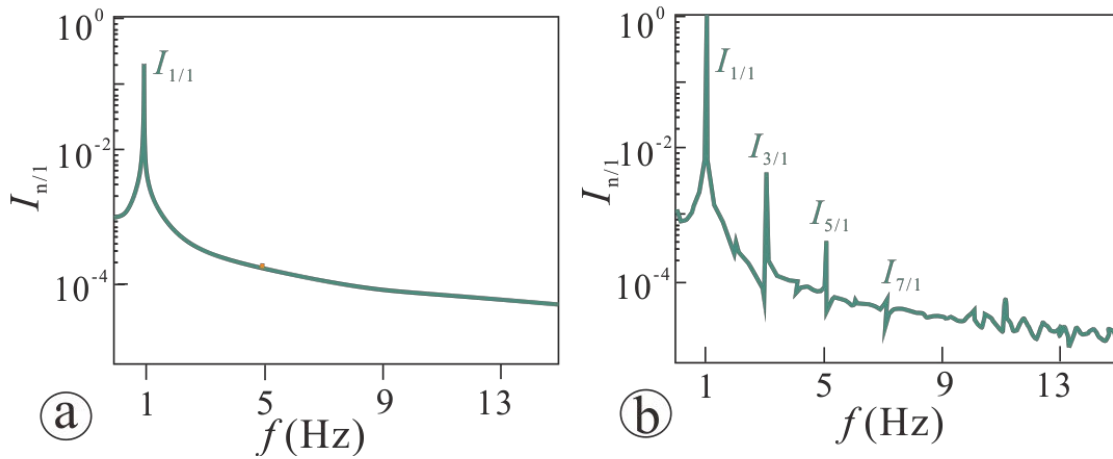


Figure 2. Representative Fourier spectra of the stress response under LAOS in **(a)** the linear viscoelastic regime and **(b)** the nonlinear viscoelastic regime.

The relative intensity of the n th harmonic, I_n/I_1 , quantifies the nonlinear contribution to the stress response. In particular, I_3/I_1 is widely used to identify the onset and development of nonlinear viscoelasticity (Hyun *et al.* 2011). Stress decomposition provides complementary information by separating recoverable strain associated with elastic deformation from unrecoverable strain associated with plastic flow (Cho *et al.* 2005; Rogers *et al.* 2011, 2012; Donley *et al.* 2020). These methods are suitable for describing the progressive solid liquid transition of loess mudflows under LAOS.

The nonlinear characteristic coefficient Q is defined in Equation (7) according to the scaling relationship between I_3/I_1 and strain amplitude (Hyun *et al.* 2011).

$$Q = I_{3/1} / \gamma_0^2 \quad (7)$$

Q amplifies subtle changes in the strain dependence of the third harmonic response. Q_0 denotes the limiting plateau value of Q at the lowest strain amplitude and represents the intrinsic weakly nonlinear response under a specified water content and frequency. The nonlinear elastic and viscous moduli used in the Fourier analysis are obtained from the harmonic response, with the frequency dependence expressed through the angular frequency and shear rate relationship (Giacomin *et al.* 2011).

3. Method and materials

3.1. Sample preparation

The study area is located in Caotan Village, Zhongchuan Township, Gansu Province. On 18 December 2023, a magnitude 6.2 earthquake struck Jishishan County and triggered a large loess liquefaction flow slide in Caotan

Village. The failed mass travelled a considerable distance and produced typical geomorphic features associated with loess liquefaction flow slides. Field surveys showed that the source material was primarily Quaternary loess. The liquefied material was dark brown, saturated, and spatially heterogeneous. Following the principles of similarity theory, undisturbed soil was collected from the source zone for laboratory testing. Particle size analysis indicated that the sample was dominated by fine particles, with clay and silt contents of approximately 4.89% and 80.64%, respectively. The median particle size is 21.8 micrometers. The measured natural moisture content is 19.7%, while the plasticity and liquid limit are 21.7% and 29.3% respectively (Figure 3a). These indicators indicate that this material belongs to low plasticity silt, with a high silt content and limited plasticity. Its characteristics make it prone to sliding flow caused by liquefaction.

To minimize the influence of roots and organic contaminants, the collected soil was first air dried and then sieved through a 0.1 mm mesh. Based on the soil water conditions observed in the field, specimens with target water contents of 28%, 32%, and 36% were prepared to investigate the influence of water content on the nonlinear rheological response of loess mudflows. For each preparation, 100 g of distilled water was measured, and the corresponding mass of dry soil was determined using $m_s = m_w / w$, where m_s represents the mass of air dried soil, m_w is the mass of added water, and w denotes the prescribed water content. The calculated soil mass was then combined with the measured water and mixed until the material appeared uniformly blended. The total mass deviation of each specimen was kept within ± 0.50 g. Three replicate specimens were prepared for every water content to improve the reproducibility and reliability of the measurements.

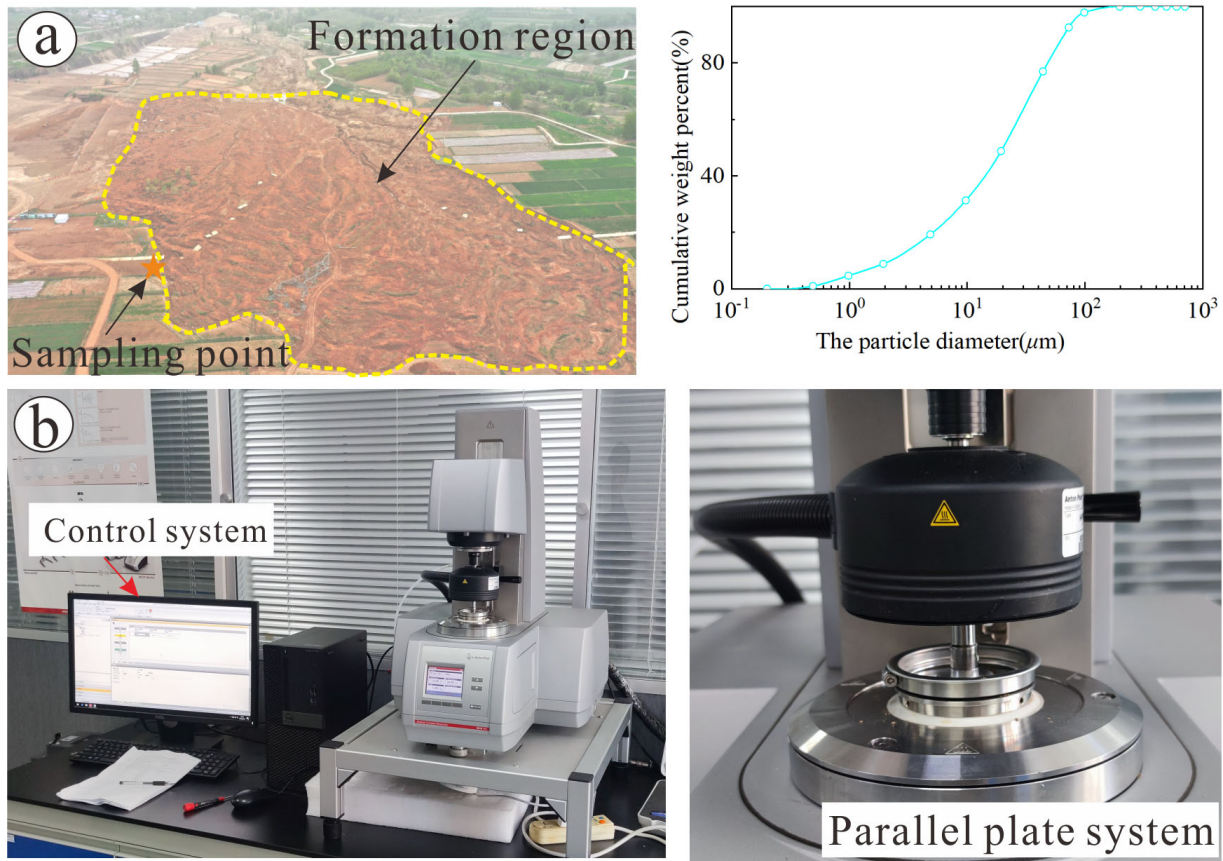


Figure 3. Sampling and experimental configuration. (a) Sampling points and gradation curves of the test samples; (b) Testing instruments.

3.2. Rheological test

An Anton Paar M702 rheometer was employed to conduct LAOS strain sweep experiments. A parallel plate system with a plate diameter of 25 mm and a separation distance of 1 mm was used. After loading each specimen between the plates, excess material was removed to minimize edge related effects and a serrated parallel plate geometry was used to minimize wall slip (Figure 3b,c). The strain amplitude was progressively increased from 0.1% to 1000% at frequencies of 0.1, 0.5, 1, 3, 5, and 10 Hz. A separate specimen was prepared for every sweep, and the temperature was maintained at 20 ± 1 °C. Considering the variability commonly associated with rheological measurements, each sample was subjected to preshearing at 50 s^{-1} for 30 s and then allowed to rest for 30 s before the test began (Jeong *et al.* 2015).

4. Results

4.1. Nonlinear rheological characteristics under large amplitude oscillatory shear

Based on the rheological curves (Figure 4), the rheological characteristics of loess mudflows can be divided into the following three stages:

(1) Linear viscoelasticity: In the initial shear stage, both the storage modulus G' and the loss modulus G'' remain at a certain constant level without changing with increasing shear strain. This region is referred to as the linear viscoelastic range (Holthusen *et al.* 2020), and the corresponding shear strain is the critical strain of the linear viscoelastic range (γ_L). In this region, G' is much larger than G'' (generally by one order of magnitude), indicating that the internal structure of the sample remains intact and the material exhibits elastic dominated solid-like behavior. Moreover, the trends of G' and G'' with strain show no significant correlation with the applied frequency.

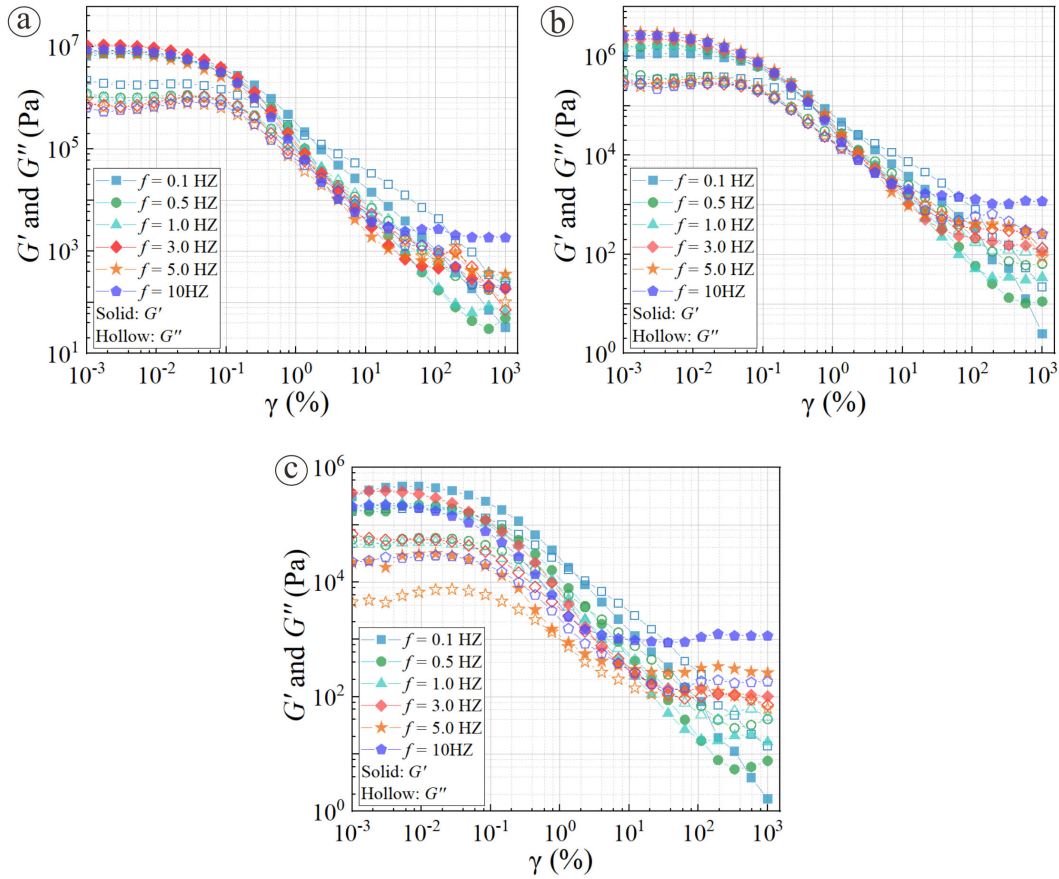


Figure 4. Large amplitude oscillatory shear rheological curves of loess mudflows under different conditions. (a) $w = 28\%$; (b) $w = 32\%$; (c) $w = 36\%$.

(2) Nonlinear viscoelastic region dominated by solid-like characteristics: As the shear strain further increases, G' begins to gradually decrease, and the loess mudflow exhibits nonlinear viscoelastic behavior. G'' first increases with increasing shear strain to a certain maximum value, showing an overshoot characteristic, and then gradually decreases with further increase in shear strain. During this process, the structure of the loess mudflow undergoes irreversible deformation and structural breakdown. When the shear strain increases to a certain value, G' and G'' intersect. Before this intersection point, G' is always greater than G'' , and the loess mudflow mainly exhibits elastic-dominated viscoelastic behavior. The shear stress corresponding to this intersection point is defined as the yield stress (Holthusen *et al.* 2020), at which the loess mudflow undergoes a solid to fluid transition.

(3) Nonlinear viscoelastic region dominated by fluid-like characteristics: As the shear strain further increases, G' becomes smaller than G'' , and both G' and G'' decrease by nearly five orders of magnitude. In this region, the loess mudflow is dominated by viscous behavior, exhibiting viscosity-dominated viscoelasticity and showing viscous flow behavior. It is worth noting that at a water content of 36% and frequencies of 5 and 10 Hz, G' remains greater than G'' throughout, indicating that a high water content combined with high frequency consistently exhibits solid-like characteristics.

To more accurately quantify the nonlinear rheological characteristics of loess mudflows, this study defines four viscoelastic characteristic parameters: the critical shear strain of the linear viscoelastic region, the nonlinear limit point (corresponding to the peak of the loss modulus G''), the nonlinear transition point (defined by the deviation at which the storage modulus G' decreases by 5%), and the shear strain at the solid-liquid transition point (the shear strain corresponding to the crossover of G' and G'') (Table 1).

Figure 5 shows the variation of these parameters with frequency: the shear strain of the linear viscoelastic region and the shear strain at the nonlinear transition point gradually decrease with increasing frequency, while the shear strain at the nonlinear limit point and the shear strain at the solid-liquid transition point gradually increase with increasing frequency. It is worth noting that 1 Hz is a critical transition frequency. When the frequency increases from 0.1 Hz to 1 Hz (within the range below 1 Hz), the decreases in the critical shear strain of the linear viscoelastic region and the shear strain at the nonlinear transition point both exceed 40%, and this decrease becomes more pronounced with increasing water content. When the frequency exceeds 1 Hz, the decreases in both parameters become gentler, and the differences among different water content conditions are significantly reduced, indicating that within this frequency range, the dependence of the

linear viscoelastic region and the nonlinear transition point on water content is markedly weakened. Similarly, in the frequency range below 1 Hz, the increases in the shear strain at the nonlinear limit point and the shear strain at the solid-liquid transition point are relatively small (only about 4%), with weak dependence on water content; the values under the three water content conditions are relatively close.

However, as the frequency further increases (from 1 Hz to 10 Hz), the dependence of these two parameters on frequency and water content becomes significantly stronger. Specifically, the increase in the nonlinear

limit point exceeds 140%, and its magnitude decreases significantly with increasing water content; whereas the increase in the solid-liquid transition point increases markedly with increasing water content. Particularly at a water content of 36%, the increase reaches as high as 450%, approximately 15 times that under the conditions of 28% and 32% water content. These results indicate that under high water content and high frequency conditions, a larger critical shear strain is required for the phase transition of loess mudflows.

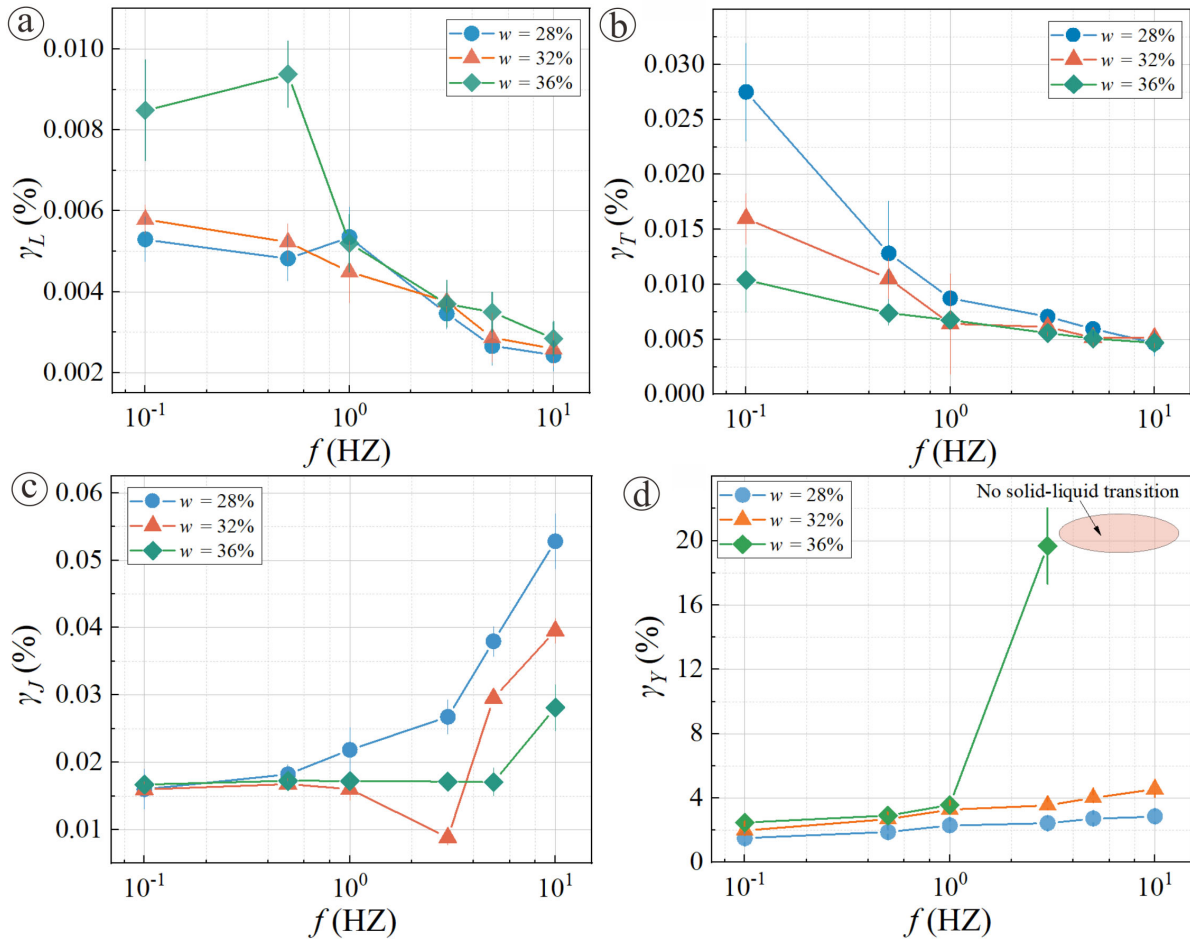


Figure 5. Variation characteristics of viscoelastic characteristic parameters under different conditions. **(a)** Shear strain of the linear viscoelastic region; **(b)** Shear strain at the nonlinear transition point; **(c)** Shear strain at the nonlinear limit point; **(d)** Shear strain at the solid-liquid transition point.

Table 1. Physical interpretations of the viscoelastic characteristic strains.

Number	Parameter	Unit	Physical interpretation
1	γ_L	%	Shear strain of the linear viscoelastic region
2	γ_T	%	Shear strain at the nonlinear transition point (defined by the deviation at which the storage modulus G' decreases by 5%)
3	γ_J	%	Shear strain at the nonlinear limit point (corresponding to the peak of the loss modulus G'')
4	γ_Y	%	Shear strain at the solid-liquid transition point (the shear strain corresponding to the crossover of G' and G'')

4.2. Nonlinear rheological characteristics based on Fourier theory

4.2.1. Nonlinear stress response characteristics

During a LAOS experiment, the specimen is subjected to a sinusoidal strain, and the corresponding stress signal is recorded. The extent to which this signal departs from an ideal sinusoidal waveform provides a direct indication of nonlinear viscoelastic behavior.

Figure 6 presents the stress responses measured at a strain amplitude of 3.96% under different water contents

and frequencies. All specimens show waveform distortion from the beginning of the test, indicating that the applied strain is well beyond the linear viscoelastic limit, which is below 0.01%. At a given frequency, reducing the water content produces a more pronounced nonlinear stress response. This effect becomes less evident as the frequency increases. At high water contents, however, the response signals become more irregular at elevated frequencies. In particular, the samples with water contents of 32% and 36% display noticeable fluctuations at 10 Hz.

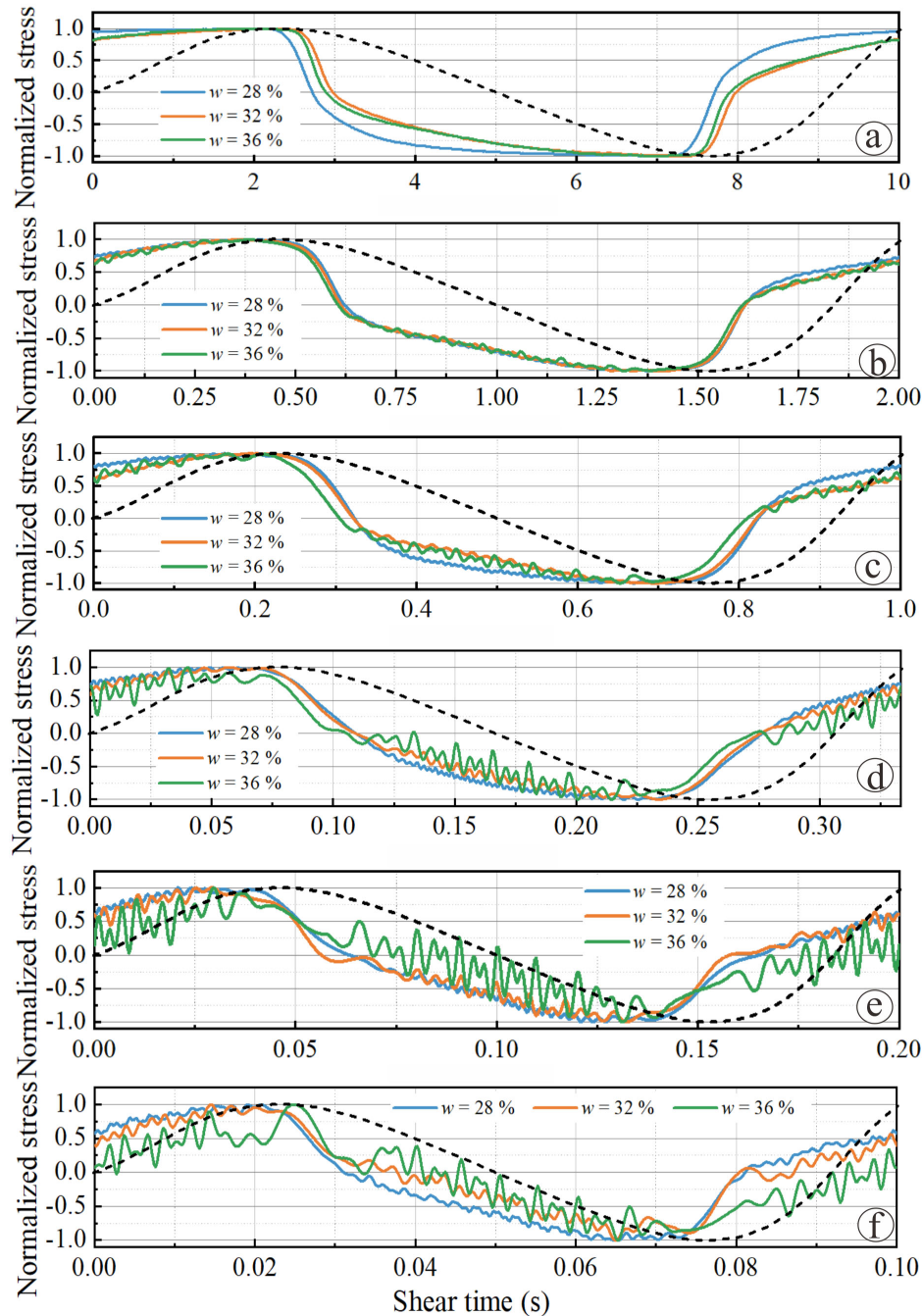


Figure 6. S Stress responses at a fixed strain amplitude of $\gamma_0 = 3.96\%$ under different water contents and oscillation frequencies. (a) $f = 0.1$ Hz; (b) $f = 0.5$ Hz; (c) $f = 1$ Hz; (d) $f = 3$ Hz; (e) $f = 5$ Hz; (g) $f = 10$ Hz.

Figure 7 compares the stress responses obtained at different frequencies under the same strain amplitude and water content. As the frequency decreases, the waveform distortion increases, indicating that low-frequency loading can promote a stronger nonlinear viscoelastic response. This frequency dependence is particularly evident in the samples with a water content of 28%, where the

response curves show significant differences among different testing frequencies. For samples with water contents of 32% and 36%, the changes in waveform distortion caused by frequency are relatively small. These results suggest that when the water content is relatively low, the nonlinear rheological response is more sensitive to the loading frequency.

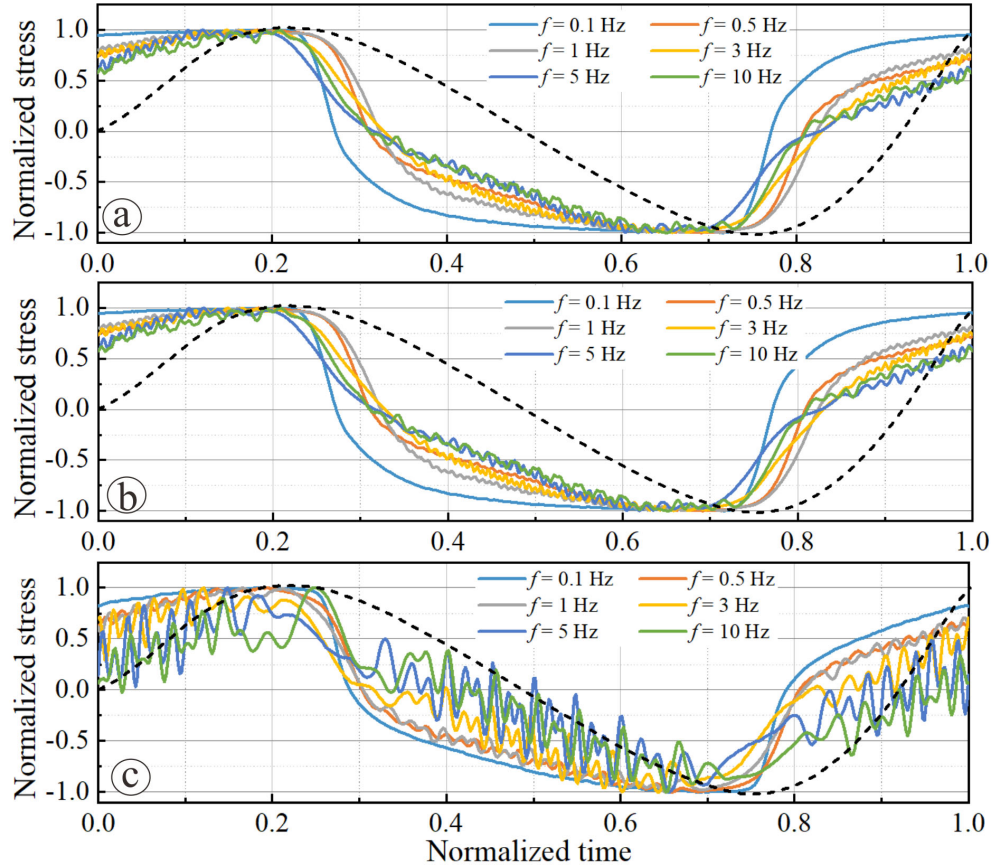


Figure 7. Stress responses of loess mudflows at $\gamma_0 = 3.96\%$ under different oscillation frequencies. (a) $w = 28\%$; (b) $w = 32\%$; (c) $w = 36\%$.

4.2.2. Nonlinear viscoelastic analysis based on higher harmonic amplitudes

From the above analysis, it is evident that the stress response waveform of loess mudflows under large amplitude oscillatory shear no longer maintains a sinusoidal shape. The core concept of Fourier rheology is to treat this response waveform as a superposition of waveforms at multiple integer multiples of the fundamental frequency. By analyzing the variation of the relative intensity of higher harmonics (I_n/I_1) with oscillatory strain amplitude, the nonlinear characteristics of the soil can be described. Figure 8 shows the variation of I_n/I_1 with strain amplitude for loess mudflows under different water content conditions.

Within the small strain amplitude range, the relative intensity of higher harmonics approaches zero, corresponding to ideal linear viscoelastic behavior. When the strain amplitude exceeds a certain threshold,

the third harmonic relative intensity (I_3/I_1) begins to gradually increase with increasing strain amplitude, marking the onset of nonlinear viscoelastic behavior. The critical strain amplitudes for water contents of 28%, 32%, and 36% are 0.191%, 0.074%, and 0.035%, respectively. Comparing the results of storage/loss modulus analysis with those of Fourier rheology analysis, it can be found that the critical strain amplitude for the linear-nonlinear viscoelastic transition identified by the Fourier rheology method is always higher than that obtained from storage/loss modulus analysis. This indicates that when the soil microstructure is slightly damaged (when the storage modulus begins to decrease with increasing strain amplitude), the soil can still maintain linear viscoelastic characteristics to some extent. It also demonstrates that the Fourier rheology method is more sensitive than storage/loss modulus analysis in detecting the transition from linear to nonlinear viscoelasticity.

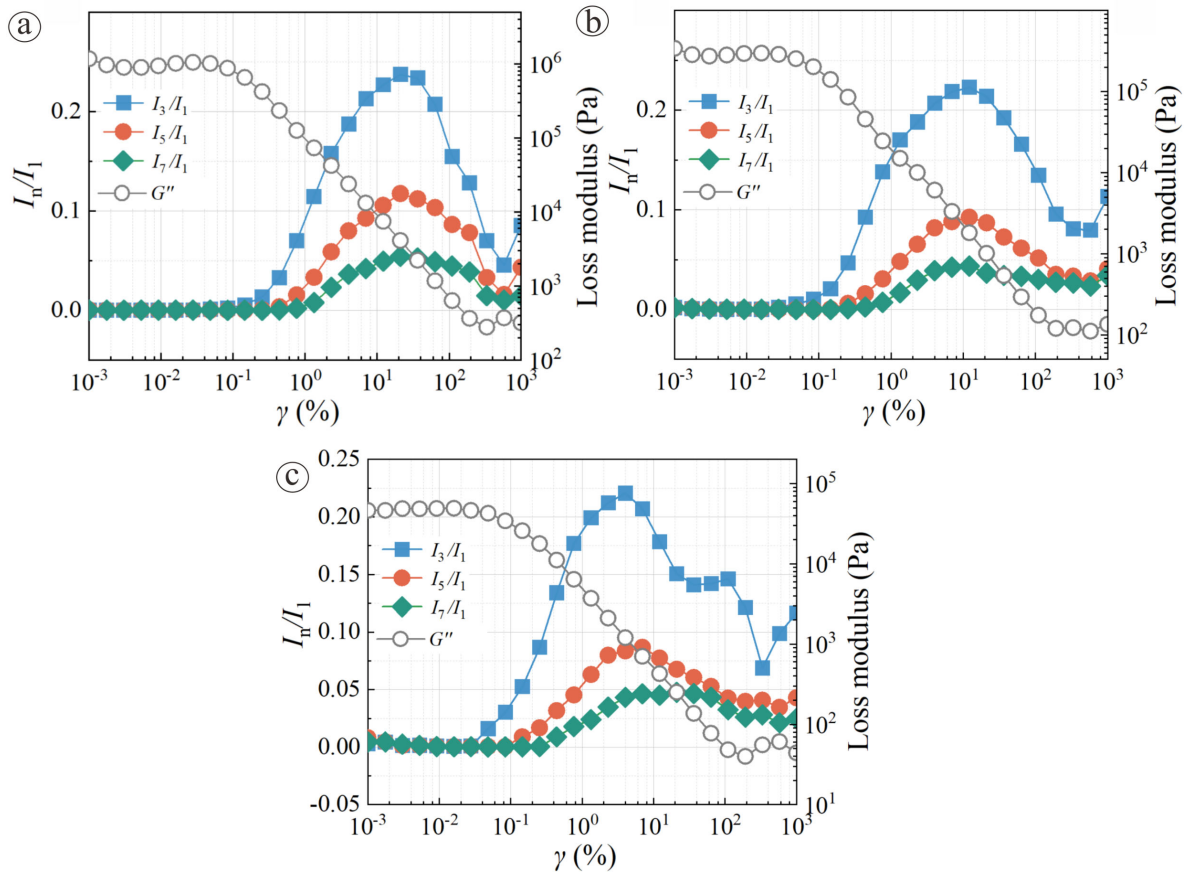


Figure 8. Relative higher-harmonic intensities I_n/I_1 as functions of strain amplitude at $f = 1$ Hz. **(a)** $w = 28\%$; **(b)** $w = 32\%$; **(c)** $w = 36\%$.

On the other hand, as shown in Figure 8, after entering the nonlinear viscoelastic regime, higher harmonics (I_5/I_1 , I_7/I_1) gradually appear with further increase in strain amplitude, indicating that the increase in strain amplitude induces stronger nonlinear viscoelastic behavior of the soil. When the strain amplitude continues to increase and exceeds a certain critical value, the third harmonic relative intensity (I_3/I_1) rapidly decreases after reaching a peak. The critical strain amplitudes for water contents of 28%, 32%, and 36% are 21.55%, 11.21%, and 3.66%, respectively. Rogers *et al.* 2011, 2012) attributed this post peak decrease to the high shear rate power-law fluid response induced by high shear strain at a constant oscillation frequency. It is worth noting that at a water content of 36%, I_3/I_1 exhibits a complex variation of first increasing, then decreasing, and then increasing again after entering the nonlinear viscoelastic regime. A possible explanation or this phenomenon is that under high water content conditions, the larger disrupted chain-like structures rearrange to form cluster structures, and when the strain amplitude reaches 112.17%, these cluster structures break again.

In Fourier transform LAOS rheological analysis, the nonlinear characteristic coefficient Q can be used to

describe the transition of a material from the linear to the nonlinear regime. As shown in Figure 9, when the strain amplitude is less than 1, the Q value remains in a relatively stable plateau region, essentially unchanged, indicating that the soil exhibits good elastic behavior and its internal structure undergoes no significant variation. With a further increase in strain, the Q value rapidly decreases and follows a certain power-law decay pattern, indicating that the rheological properties of the soil have begun to change and the nonlinear viscoelasticity gradually strengthens. Under the same shear strain condition, the Q value decreases with increasing frequency, suggesting that low-frequency loading is more likely to cause shear failure in the soil, and the nonlinear characteristics are more pronounced. Moreover, under small strain conditions, the dependence of Q on frequency is particularly prominent, with differences in Q values across frequencies reaching up to four orders of magnitude. As the shear strain increases, this frequency dependence gradually weakens, and the gaps in Q values under different frequency conditions continuously narrow, indicating that under large strain conditions, the flow characteristics of samples at different frequencies tend to converge.

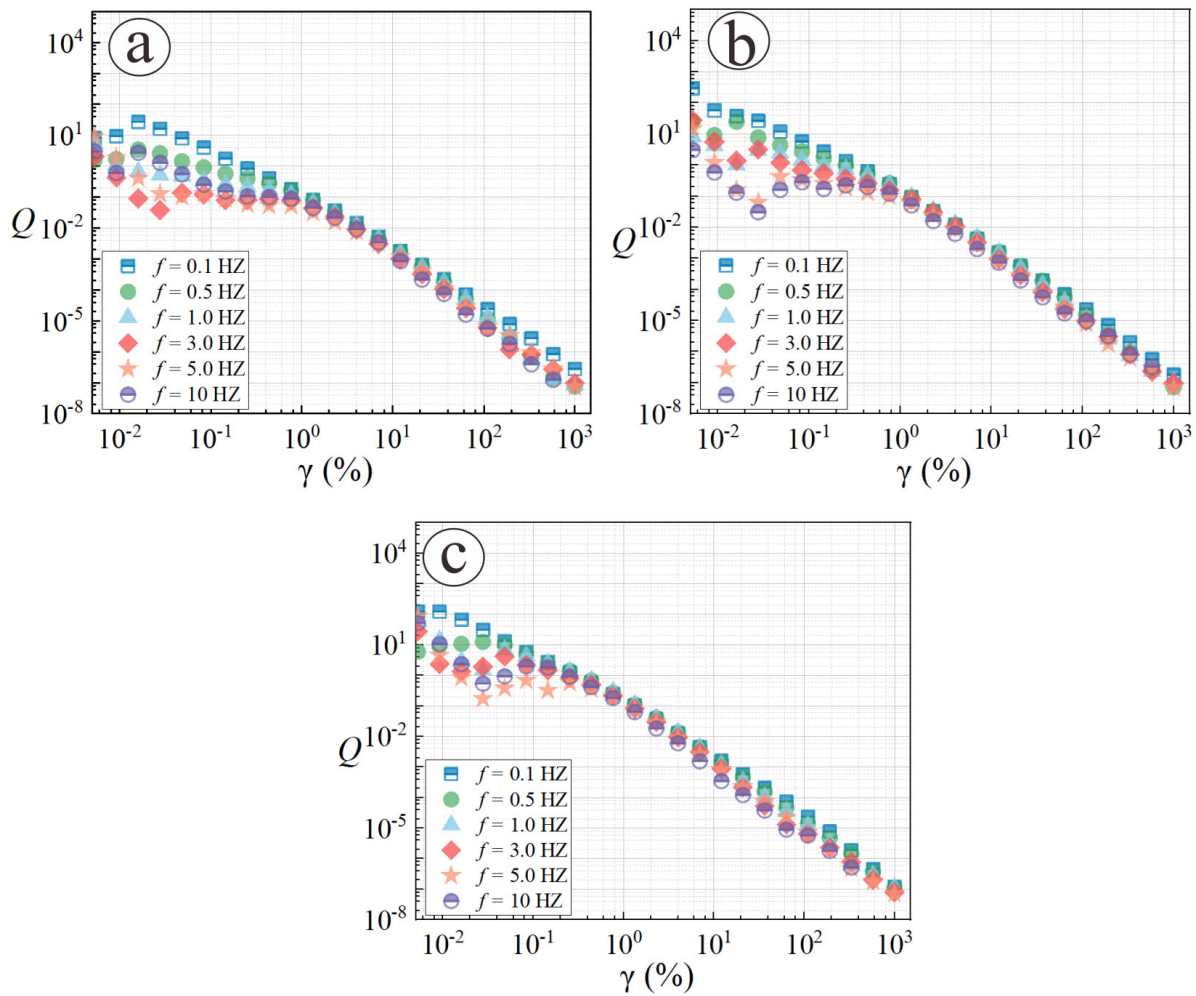


Figure 9. Variation characteristics of the nonlinear characteristic coefficient with strain amplitude for loess mudflows under different water content conditions. **(a)** $w = 28\%$; **(b)** $w = 32\%$; **(c)** $w = 36\%$.

5 Discussion

5.1. Analysis of factors influencing soil nonlinearity

The experimental results show that water content strongly regulates the nonlinear rheology of loess mudflows (Wang *et al.* 2020). Increasing water content from 28% to 36% weakens the nonlinear response, as indicated by a smaller linear viscoelastic limit, and a higher strain requirement for the solid liquid transition (Figure 5 and 8).

This trend may be related to the changes in particle structure caused by water. As the water content increases, the soil skeleton expands, the particle spacing increases, and the connectivity of the contact network weakens. The pore area ratio rises from 12.1% to 20.3%, while the fractal dimension of the aggregates decreases from 1.47 to 1.13 when the water content increases from 24% to 36% (Figure 10). These changes indicate that the structure is transforming from dense, highly branched aggregates to a more dispersed structure (Hou *et al.* 2021; Chen *et al.* 2021; Lourenço *et al.* 2012). The resulting structure stores and releases

elastic energy during the shear process, which may explain its relatively weak nonlinear response (Lian *et al.* 2022). Additionally, water forms hydration films around the particles, weakening van der Waals forces, particle interlocking, and friction (Li *et al.* 2022; Lancaster, 1990). These changes facilitate particle sliding, which is consistent with the observed weak nonlinear response and higher solid-liquid transition strain at 32% and 36% water content. The loading frequency further affects this response characteristic. At 36% water content, increasing the loading frequency from 1 Hz to 10 Hz increases the solid-liquid transition strain by approximately 450%, which is nearly 15 times the increase observed at 28% and 32%. Rapid loading leads to an increase in pore water pressure and insufficient drainage, which may result in a decrease in effective stress and a transient non-discharge response, thereby delaying the structural failure and liquefaction process (Lian *et al.* 2022; Wang *et al.* 2026a). Frequency also affects the time scale of nonlinear deformation (Dong *et al.* 2025; Xiao *et al.* 2024). When the frequency is below 1 Hz, the linear limit and nonlinear transition strain significantly decrease, especially under higher water content conditions. These changes gradually weaken as the frequency increases (Figure 5).

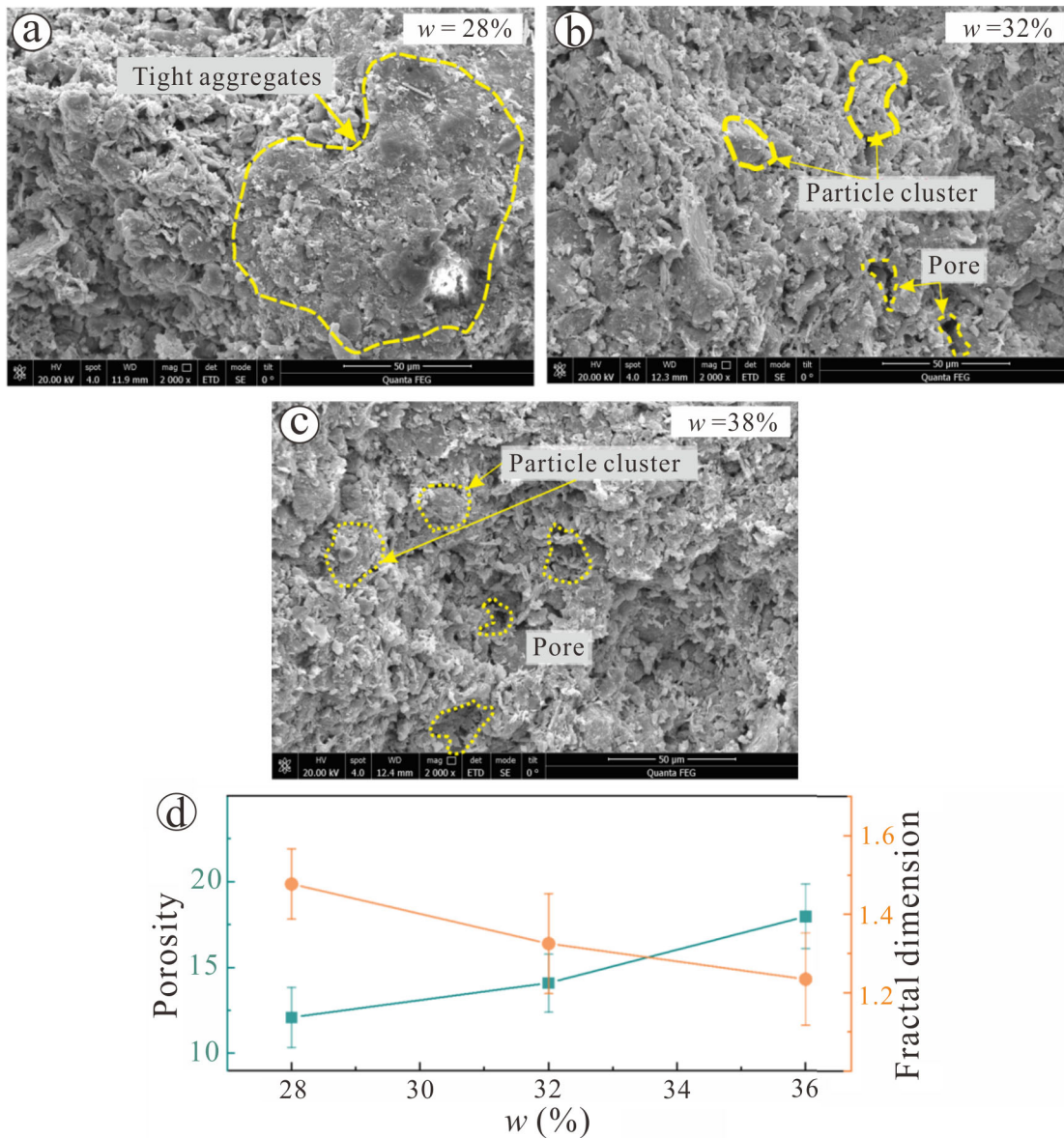


Figure 10. SEM images of soil sample and the quantitative analysis of microstructural. (a–c) $w=28\%$, 32% , 36% ; (d) The variation of particle fractal dimension and porosity with water content.

From a micro-dynamic perspective, low-frequency loading can allow particles to overcome local energy barriers for diffusion and rearrangement, leading to progressive structural failure and a pronounced nonlinear response. Under such conditions, loess mudflows require the accumulation of sufficient strain to complete the transition from local damage to bulk flow (Bonn *et al.* 2017). In contrast, under high-frequency loading, particle motion is constrained by the limited response time, resulting in weak nonlinearity. From the perspective of the Deborah number ($De = \lambda(\dot{\gamma}) * \omega$), where $\lambda(\dot{\gamma})$ is the shear rate dependent relaxation time (Giacomin *et al.* 2011), under low-frequency conditions the Deborah number is small, the relaxation time is shorter than the observation time scale, and the material exhibits more fluid-like behavior, allowing accumulation of unrecoverable strain. At high frequencies, Deborah number is larger, and the relaxation time exceeds the

observation time scale. The material does not have enough time for relaxation, and thus exhibits a response similar to that of a solid. This is consistent with the observation results of this study: at high frequencies (10 Hz), even with a high water content (36%), the storage modulus G' is still greater than the loss modulus G'' , and the material continues to exhibit characteristics similar to those of a solid (Figure 5).

Furthermore, there is a clear coupling effect between water content and frequency on the nonlinear behavior of loess mudflows. At low water content (28%), the nonlinear behavior of the material has a stronger dependence on frequency, and the deviation of the response curves at different frequencies shows significant differences. However, at high water contents (32% and 36%), this frequency dependence significantly weakens. The research by (Donley *et al.* 2020) also indicates that the sudden change in loss modulus is

caused by the internal structure of the system and external loading conditions.

5.2. Implications of nonlinear rheology for the phase transition dynamics of loess mudflows

The solid-liquid phase transition of loess mudflows is a critical process that marks the transition from a stationary state to a catastrophic movement. The dynamic mechanism of this transition directly affects the initiation conditions, duration of movement, and scale of the disaster of the mudflow (Wang *et al.* 2024). From the perspective of the mechanism of slurry occurrence, this finding supports the progressive instability theory: the initiation of a landslide or mudflow does not occur instantaneously, but gradually

propagates within the slope (Schaible *et al.* 2025). In the initial stage, shear bands first form in the stress concentration areas (such as the slope foot). Within this shear band, plastic flow dissipation dominates, resulting in irreversible plastic deformation; however, outside the shear band, the material still exhibits elastic response. As deformation continues to increase, the shear band gradually expands upward, eventually triggering the initiation of the mudflow (Figure 11). Traditional models simplify the mudflow as a homogeneous fluid and ignore the “solid residue” present during its flow (Major *et al.* 1992; Breard *et al.* 2024). Even during the high-speed movement stage, there are still elastic agglomerated structures within the mudflow; these structures continuously fracture and reorganize during the movement process, thereby dissipating energy and affecting the flow distance (Gemant 1936; Donley *et al.* 2020; Kamani *et al.* 2021).

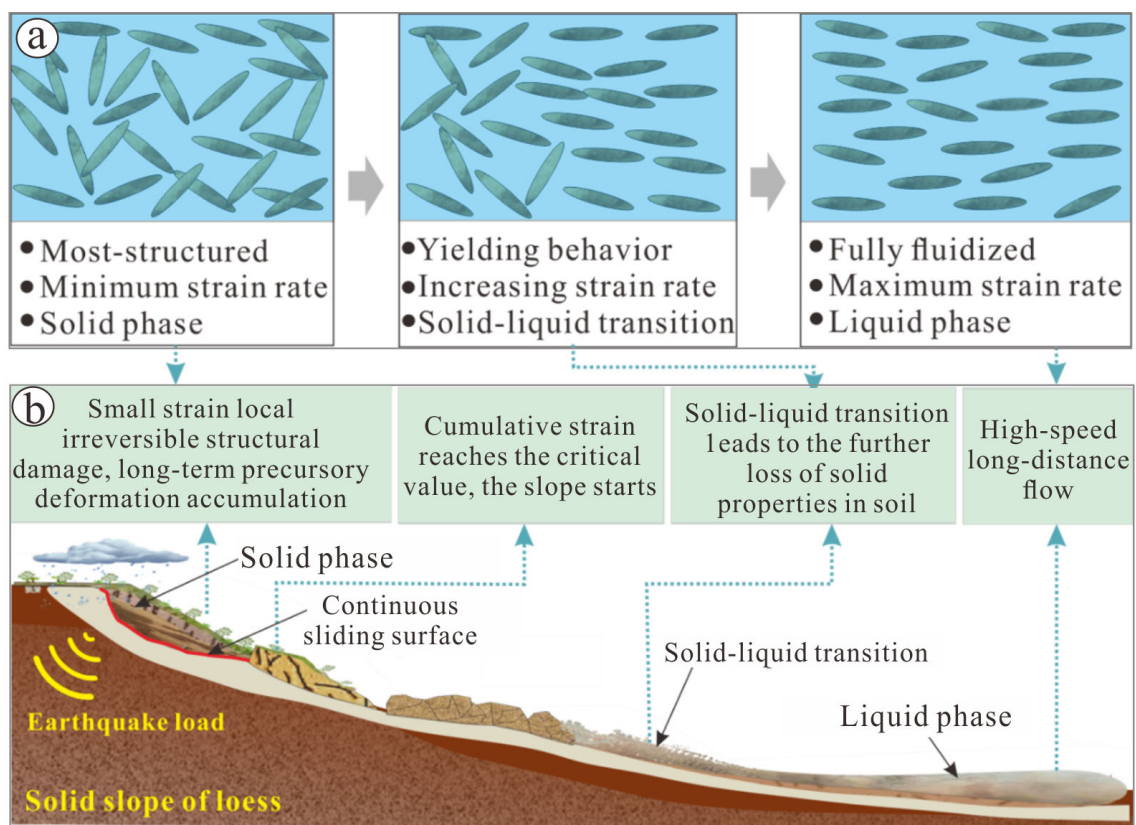


Figure 11. Conceptual interpretation of the nonlinear phase transition of loess mudflows. **(a)** Schematic diagram of microstructural evolution and rheological transition of loess mudflows; **(b)** Schematic diagram of the phase transition dynamics mechanism of loess mudflows under large amplitude oscillatory shear.

5.3. Limitations and future directions

The laboratory rheological response may be influenced by particle concentration, material structure, loading history, and test geometry, which limits the direct application of laboratory parameters to geophysical flows (Sumita *et al.* 2008; Holthusen *et al.* 2020; Costanzo *et al.* 2024). Natural mudflows have spatially varying particle size distribution, water content, structure, entrained debris, and pore pressure conditions, and

their fluidity is also affected by interactions with the substrate and shear-induced fluidization effects (Peng *et al.* 2018; Hu *et al.* 2022; Wang *et al.* 2025b). Therefore, the identified characteristic strain and 1 Hz transition frequency identified here should not be directly used for the judgment of the initial threshold at the field scale without independent verification. Although wall slip was minimized through rough plates and gap-dependent checks, the quantitative assessment of edge vector and residual slip remains challenging, which is a recognized

problem in nonlinear shear rheology (Hyun *et al.* 2011; Costanzo *et al.* 2024). The initiation and flow of loess landslides also depend on hydrogeological conditions and liquefaction processes, so the current rheological indicators need to be compared with slot experiments and field observations results (Ma *et al.* 2022; Zhang *et al.* 2022; Wang *et al.* 2025a). Therefore, the association between the proposed rheological features and field precursors should be regarded as a verifiable mechanistic hypothesis rather than a universal predictive standard, which is in line with the need to compare the rheological changes in the laboratory with independent geophysical monitoring signals for verification (Mainsant *et al.* 2012; Toney *et al.* 2026). Future research should collect loess samples from multiple source areas, expand the range of particle size and hydrogeological conditions, use complementary geometric shapes or gap-dependent measurements to quantify the sliding process, and further explore the quantitative relationship between rheological parameters (nonlinear limit points, solid-liquid transition points) and measurable field physical quantities (surface displacement rate, microseismic signals) (Zhang *et al.* 2024; Toney *et al.* 2026), thereby promoting the transformation of rheological theory to engineering practice.

4. Conclusion

This study employed large-amplitude oscillatory shear and Fourier transform rheological techniques to investigate the nonlinear rheological behavior and solid-liquid transition process of loess slurry with water contents of 28%, 32%, and 36% at oscillation frequencies ranging from 0.1 to 10 Hz. The main conclusions are as follows:

(1) With increasing strain, loess mudflow shifts from linear behavior to solid-like nonlinear behavior, then to fluid-like behavior. Four characteristic strains quantify yielding and the solid-liquid transition.

(2) Frequency strongly regulates the transition. Increasing frequency lowers the linear limit and nonlinear transition strain, but raises the nonlinear limit and solid-liquid transition strain. 1 Hz is a critical frequency; below 1 Hz the strains change sharply, while above 1 Hz the changes weaken.

(3) Higher water content weakens the nonlinear response but increases the strain required for complete liquefaction. At 36% water content and 5–10 Hz, G' remains above G'' and no solid-liquid transition occurs. Low-frequency loading enhances nonlinearity, whereas high-frequency loading favors a more solid-like response.

(4) Q is sensitive to strain, water content, and frequency, especially at small strains. SEM shows that higher water content disperses the soil structure and weakens interparticle interactions, explaining weaker nonlinearity and delayed fluidization.

Data availability statement

The data or datasets that support the findings of this study can be obtained at <https://doi.org/10.6084/m9.figshare.34012722>.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used Grammarly only to improve language and readability in limited sections of the manuscript. Generative AI was not used for data generation, data analysis, interpretation of results, or the development of scientific conclusions. The authors take full responsibility for the content of the manuscript.

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Authors' contribution

Conceptualization, D.W., X.W., J.W. and D.S.; Data curation, D.W.; funding acquisition, X.W. and D.W.; investigation, D.W., X.W. and R.L.; methodology, D.W. and D.S.; supervision, J.W. and P.J.; validation, X.W. and J.W.; Writing—original draft, D.W.; Writing—review and editing, D.W., J.W. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

Jiading Wang holds the position of Editorial Board Member for *Continuum and Life Evolution* and has not peer reviewed or made any editorial decisions for this paper. The authors declare no other conflicts of interest.

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