Research Article

Dynamic Behavior and Constitutive Relationship of Mudstone Slip Zone of Landslide with Weak Interlayer

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Sliding zone dynamics in the Qinling-Daba mountain area under different dynamic parameters have not been studied extensively. In this study, we investigated the dynamic behavior of the sliding zones of a high-steep rock landslide in the Qinling-Daba mountain area under the influence of dynamic stress amplitude and frequency and proposed an empirical model of the dynamic constitutive relationship. The dynamic behavior was studied based on a cyclic triaxial test system. The results indicated that an increase in the dynamic stress amplitude decreased the dynamic elastic modulus linearly, increased the damping ratio, and increased the axial strain exponentially. Among these properties, the elastic strain was found to be more sensitive to the increase in the dynamic stress amplitude than the plastic strain. As the loading frequency increased, the dynamic elastic modulus increased, whereas the damping ratio decreased. Furthermore, the proposed empirical model of the dynamic constitutive relationship between the vibration number and loading frequency based on the dynamic elastic modulus could satisfactorily describe the dynamic stress-strain relationships of the samples from test stability and failure zones. These findings are expected to make a significant contribution toward further revealing the sliding mechanism of such landslides.

1. Introduction

Landslides frequently occur in the Qinling-Daba mountain area, which is located south of the Shaanxi Province and north of the Sichuan Province in China. This is subjected to its unique environmental conditions and human activities [1, 2]. The Qinling-Daba mountain area is characterized by steep topography, various strata and lithology, and soft rocks and joints (structural planes). Moreover, it has strong regional tectonic activity, resulting in frequent earthquakes. Additionally, its slopes are disturbed by drilling, blasting, mechanical excavation, and other dynamic loads caused by mining, road construction, and other engineering activities. These factors promote the occurrence of geological disasters, such as landslides. Landslides caused by vibrations can result in severe property damage and casualties [3–6]. For instance, on August 12, 2015, a $168 \times 10^4 \text{ m}^3$ slope failure occurred in Shanyang County, Shaanxi Province, China, resulting in 65 deaths and an economic loss of 500 million yuan [7].

Therefore, it is necessary to study the dynamic deformation characteristics of the sliding zones of a landslide to identify the underlying mechanism.

In recent years, there have been an increasing number of studies on the dynamic deformation characteristics of rocks and soil [8–11]. Anupam et al. [12] used fly ash and rice husk ash to investigate the deformation behavior of subgrade soil mixtures under repeated triaxial loading. Mu et al. [13] analyzed the influence of different dynamic stresses and confining pressures on the cumulative deformation law of red clay in subgrade engineering to determine the critical dynamic stress range under a low confining pressure. Wichtmann et al. [14] studied the effects of strain amplitude, average stress, and the number of load cycles on the accumulation rate by conducting numerous drained cyclic tests under triaxial extension. Touqan et al. [15] conducted consolidated drained cyclic triaxial tests to simulate the long-term response of a fouled railway substructure under progressive repetitive loading and unloading cycles. Zhuang et al. [16, 17] conducted a series of dynamic triaxial tests on

expansive soils in foundation engineering using a GDS and found that the dynamic modulus of elasticity increased and the damping ratio decreased the increase in the confining pressure and consolidation stress ratio. By studying the plastic deformation behavior of the fine-grained soils under intermittent cyclic loading, Nie et al. [18] found that intermittent loading could significantly retard the development of plastic strain. Yoshinaka et al. [19] performed cyclic triaxial tests on four saturated Miocene soft rocks from Japan to study the deformation behavior, pore pressure variation, strength mobilization, and contraction/dilation characteristics. Zhang et al. [20, 21] conducted cyclic triaxial tests on loess and weathered red mudstone to obtain the stress-strain characteristics of undisturbed soil under repeated loading. In addition, Rabczuk and Ren [22, 23] proposed some numerical methods to study the crack distribution mode of materials under dynamic action, thereby providing a basis for research on the cumulative damage of different materials during dynamics. Vu-Bac et al. [24] provided a toolbox for sensitivity analysis to quantify uncertain input parameters in such numerical studies. The abovementioned studies highlight the need for investigating the dynamic characteristics of rocks and soils in the subgrade, foundation, and other civil engineering projects. Concurrently, findings have been reported on the influence of landslides under vibration [25]. Zhu et al. [26, 27] conducted a detailed field investigation and a series of dynamic triaxial tests to examine the dynamic characteristics of different staggered zones in the sliding belts of the Daguangbao landslide. They found that the dynamic elastic modulus and damping ratio were significantly affected by the material composition. Xu et al. [28] found that under seismic loading, intercalations rapidly caused greater cumulative deformation and fatigue damage than those of a surrounding rock mass. Song et al. [29] examined the influence of water content on the dynamic characteristics of a sliding zone using dynamic triaxial tests. However, the abovementioned studies are focused on the dynamic characteristics of sliding zones with different materials, moisture contents, and structural plane angles. There are relatively fewer studies on the deformation characteristics of a sliding zone in the weak interlayer of a landslide under cyclic dynamic loads with varying stress amplitudes and frequencies. Therefore, it is necessary to conduct relevant investigations in this regard.

In this study, the authors conducted a series of cyclic dynamic loading tests using a GDS dynamic triaxial instrument to study the effects of the dynamic stress amplitude and frequency on the dynamic deformation characteristics of a sliding zone of the Shanyang landslide in Shaanxi Province, China. In addition, this study established a dynamic constitutive model of the dynamic stress-strain relationship of a sample under cyclic loading, based on the dynamic elastic modulus.

2. Test Materials and Scheme

2.1. Test Materials and Equipment. The test materials were obtained from the Shanyang landslide in Shaanxi Province in China (see Figure 1). The Shanyang landslide that occurred at 0:30 a.m. on August 12, 2015 (Beijing, UTC + 8) was caused by rainfall and long-term vibration, among other

conditions. The landslide was approximately 550 m in length, 130 m in width, 10–40 m in thickness, and $168 \times 10^4 \text{ m}^3$ in volume. The slope lies on the southeast wing of the Yaolinghe anticline with inverted strata and slope angles ranging from 42° to 55° , controlled by three sets of regional structural planes. The steep slope consists of thick dolomite from the middle Sinian Dengying group and overlies the interbedding of carbonaceous claystone and siliceous rocks from the lower Cambrian Shuigoukou group. The two sets of strata have an unconformity contact. Additionally, there are weak intercalations in the unconformity contact, mainly mudstone, which has a strong water-holding capacity. However, when the mudstone comes into contact with water, its strength abruptly decreases.

In addition, there are frequent mining activities in the landslide area. Owing to the short vertical distance between the mining roadway and weak interlayer zone (21~35 m), the Shanyang slope is continuously affected by vibrations. To understand the sliding mechanism and study the influence of vibrations on the stability of landslides, mudstone samples from the weak intercalation layer were selected to perform a series of dynamic triaxial cyclic loading tests.

Table 1 lists the physical and mechanical properties of the samples. In Table 1, ρ denotes the dry density, ω denotes the natural moisture content, W_L denotes the liquid limit, W_P denotes the plastic limit, I_P denotes the plastic index, c denotes the cohesion, and φ denotes the internal friction angle. Remolded samples were selected because of the difficulty in obtaining undisturbed mudstone. The samples were prepared based on their natural moisture content and dry density. The diameter and height of each sample were 38 mm and 80 mm, respectively.

The dynamic triaxial tests were conducted using a GDS dynamic triaxial testing system (DYNTTS) which comprises a main machine, a universal triaxial cell top, deairing block, pore pressure transducers, a GDS standard controller, and data acquisition units (see Figure 2). The detailed parameters of the GDS/DYNTTS are as follows: vertical vibration frequency of 0.01–5 Hz, the static or dynamic axial load of 0–40 kN, and confining pressure of 0–2000 kPa.

2.2. Test Scheme. Based on the Chinese National Specification (Standard for Geotechnical Testing Method, GB/T 50123-2019) [30], the dynamic loads applied in this test were repeated cyclic loads. The applied dynamic loads were sinusoidal vibration waves, and the confining pressure was 400 kPa.

First, a sample was placed in a saturator for air extraction. Subsequently, the sample was transferred to a sleeve containing a rubber diaphragm and installed on the base of the GDS apparatus to saturate for 24 h. When the B value of the specimen exceeded 0.98, the specimen was isotropically consolidated under a certain effective confining pressure. Once the water discharge was below $0.1 \text{ cm}^3/\text{h}$, the consolidation was considered to be completed. Finally, cyclic loading triaxial tests were performed under undrained conditions, and the dynamic loads were applied in stages. Vibrations were introduced 10 times at each dynamic

FIGURE 1: Sampling location map.

TABLE 1: Index properties of tested samples.

ρ (g/cm ³)	ω (%)	W_L	W_P	I_P	C (kPa)	φ (°)
1.60	30.28	39.22	24.46	14.76	51.30	16.75

FIGURE 2: GDS/DYNTTS.

loading stage. The dynamic stress amplitude and frequency were considered in this test. Table 2 lists the test scheme details, and Figure 3 illustrates the loading path of the test stress.

3. Results and Analysis

3.1. Axial Strain. The axial strain time history curve (frequency of 0.5 Hz) is illustrated in Figure 4. With the increase in time, the axial strain fluctuated with the loading waveform and

demonstrated an increasing trend overall. In the early stage, the growth rate of the axial strain was low under the vibration load with a small amplitude of the dynamic stress. At a later stage, with the increase in the dynamic stress amplitude, the growth rate of the axial strain increased gradually. When the dynamic stress amplitude exceeded a certain threshold, the axial strain increased rapidly, and the specimen was destroyed. The axial strain of the specimen under cyclic loading comprised elastic and plastic strains. The lowest point in the axial strain curve of a sample is its cumulative plastic strain, and the difference between the highest and lowest points represents the elastic strain. In Figure 4, ε_r represents the elastic strain and ε_p denotes the plastic strain. The variation curves of the elastic and plastic strains with a vibration time of 0.5 Hz are depicted in Figure 5.

As depicted in Figure 5, before the failure of the specimen, the elastic and plastic strains increased with the increase in cycle number. Their trends were consistent with those of the total axial strain. Under small-amplitude loading, the strains increased gradually. With the increase in the cycle number and amplitude, the strain growth rate increased rapidly. The elastic deformation was more rapid than the plastic deformation in the early stage of loading. With the increase in the dynamic stress amplitude and cycle number, the deformation of the specimen transitioned from the elastic to plastic deformation stage, and the plastic strain rate increased more rapidly than the elastic strain rate. Additionally, the elastic strain curve exhibited a clear climbing phenomenon, whereas the plastic strain curve was relatively smooth. Specifically, the elastic strain increased sharply when the dynamic stress amplitude increased at each stage, whereas the plastic strain did not. Therefore, the elastic strain was more sensitive to the increase in the dynamic stress

TABLE 2: Dynamic loading test scheme of mudstone sample.

Group	Confining pressure (kPa)	Frequency (Hz)	Dynamic stress amplitude
1	400	0.5	Initial value $\sigma_d = 5$ kPa, increased by 10 kPa
2	400	1	Initial value $\sigma_d = 5$ kPa, increased by 10 kPa
3	400	3	Initial value $\sigma_d = 5$ kPa, increased by 10 kPa

FIGURE 3: Schematic of triaxial cyclic loading. Note that σ_{dmax} denotes the maximum dynamic stress, σ_{dmin} denotes the minimum dynamic stress, and σ_d denotes the dynamic amplitude.

FIGURE 4: Time history curves of axial strain at 0.5 Hz.

amplitude than the plastic strain under dynamic load applications.

Figure 6 depicts a comparison of the elastic and plastic strains at different frequencies. The changing trends of both strains were similar under different frequencies. As the frequency increased, the number of cycles needed for the failure of the specimen increased, and the small strain when the specimen was damaged implied a low strain growth rate. The influence of the frequency on the strains was more significant at low frequencies than that at high frequencies, and the influence of the frequency decreased as the frequency increased.

Studies [31, 32] have found that cumulative plastic strain versus cycle number curves under cyclic dynamic loading can be classified into three types, namely, stable, critical, and

FIGURE 5: Curves of elastic and plastic strains at 0.5 Hz.

failure. The corresponding curves with the dynamic stress amplitudes under different frequencies obtained in this study are illustrated in Figure 7.

As depicted in Figure 7, the increase in the dynamic stress amplitude and cycle number increased the plastic strain rate, and the curves approached the y-axis. The dynamic stress amplitude and loading frequency significantly affected the plastic strain curve. When the loading frequencies were 0.5, 1, and 3 Hz, the transition values of the dynamic stress amplitudes from the stable zone to the critical zone were 125, 235, and 245 kPa, respectively. The corresponding transition values from the critical zone to the failure zone were 155, 275, and 305 kPa, respectively.

Based on the previous research studies [13, 31–34], equations (1)–(3) express the curves of the cumulative plastic strain versus the cycle number in the stable, critical, and failure zones, respectively.

FIGURE 6: Elastic and plastic strain curves at different frequencies. (a) Elastic strain. (b) Plastic strain.

$$\varepsilon_p = a(1 + b \lg N), \quad (1)$$

$$\varepsilon_p = AN + B, \quad (2)$$

$$\varepsilon_p = cN^d. \quad (3)$$

Here, ε_p denotes the plastic strain, n denotes the cycle number, and a , b , A , B , c , and d represent the parameters related to the dynamic stress and soil properties.

In this study, (1)–(3) were used to fit the cumulative plastic strain curves at 0.5 Hz. When the dynamic stress amplitude is varied from 75 kPa to 115 kPa, the curve type is stable, and it can be fitted by equation (1). When the dynamic stress amplitude ranges from 125 kPa to 145 kPa, the curve type is critical, and it can be fitted by equation (2). When the dynamic stress amplitude varies from 155 kPa to 185 kPa, the curve type is a failure, and it can be fitted by equation (3).

The fitting parameters are listed in Table 3, which vary under different dynamic stress amplitudes because the fitting parameters are related to the applied dynamic stress amplitudes. Equations (1)–(3) have good applicability to the test data of the stable, critical, and failure curves, and the correlation coefficients are above 0.90. The fitting effect is ideal, which indicates that the relationship between the cumulative strain and the number of cyclic vibrations under cyclic loading can be described appropriately.

3.2. Dynamic Stress-Strain Relationship. The curves of the deviator stress versus the axial strain of the samples at different frequencies are illustrated in Figure 8.

As depicted in Figure 8, when the strain was less than 3.5%, the dynamic stress increased sharply, following which

as the axial strain increased, the dynamic stress first increased gradually, subsequently tended to be stable, and finally began to decrease after reaching the peak value.

At the start of the test, the sample with intact structure and the small strain was in the elastic deformation stage, where the stress-strain curves under different frequencies were similar. As the increase of dynamic stress amplitude, the structure is gradually damaged along with slip between internal particles. In this process, the strain developed faster, shear failure gradually formed; deviator stress decreased. Meanwhile, it can be found that the greater the loading frequency is, the greater the dynamic stress is needed for the specimen reaches the same strain value. The results indicate that the increase in the frequency can restrain the development of the dynamic strain of the mudstone samples and benefit the stability of the landslide.

3.3. Dynamic Elastic Modulus. The dynamic elastic modulus, E_d , is determined as the slope of the line connecting the two ends of the hysteresis loop in the dynamic stress-strain curve:

$$E_d = \frac{\sigma_{d\max} - \sigma_{d\min}}{\varepsilon_{d\max} - \varepsilon_{d\min}}, \quad (4)$$

where $\sigma_{d\max}$ and $\sigma_{d\min}$ denote the maximum and minimum dynamic stresses in a single loading cycle, respectively, and $\varepsilon_{d\max}$ and $\varepsilon_{d\min}$ represent the maximum and minimum dynamic strains in a single loading cycle, respectively.

The E_d – σ_d obtained from the dynamic elastic modulus of the fifth cyclic loading under each loading level and the corresponding dynamic stress amplitude are depicted in Figure 9.

Figure 9 shows that the dynamic elastic modulus of the mudstone decreases almost linearly with the increase in the

FIGURE 7: Curves of cumulative plastic strain versus cycle number for different frequencies. (a) 0.5 Hz. (b) 1 Hz. (c) 3 Hz.

dynamic stress amplitude. A small frequency implies a rapid linear decrease in the dynamic elastic modulus. For the same dynamic stress amplitude, it can be observed from Figure 8 that a large loading frequency implies a large dynamic elastic modulus. The reason is that under a constant amplitude cyclic load, the higher the frequency, the faster the dynamic loading rate, and the axial deformation is too late to produce. From a microscopic perspective, the instantaneous deformation is small, whereas from the macroscopic perspective,

the dynamic elastic modulus increases with the increase in frequency [17].

Additionally, this study analyzed the change in the dynamic elastic modulus with the cycle number. Consider the E_d-N curve (see Figure 10) at a frequency of 1 Hz as an example. The dynamic elastic modulus of the sample increased with the increase in the number of cycles under a small dynamic stress amplitude. When the dynamic stress amplitude increased, the rate of increase of the dynamic

TABLE 3: Fitting of cumulative deformation curve with a frequency of 0.5 Hz.

Dynamic stress amplitude (kPa)	Fitting parameter		R^2	Curve type
75	$a = 0.0609$	$b = 2.84697$	0.98048	Stable
85	$a = 0.05071$	$b = 4.27911$	0.98918	
95	$a = 0.05085$	$b = 5.53616$	0.99279	
105	$a = 0.04962$	$b = 7.86$	0.99598	
115	$a = 0.0447$	$b = 13.12821$	0.99838	
125	$A = 0.08505$	$B = 0.10293$	0.99816	Critical
135	$A = 0.03743$	$B = 0.11785$	0.9997	
145	$A = 0.03293$	$B = 0.15219$	0.99984	
155	$c = 0.22034$	$d = 0.96399$	0.97206	Failure
165	$c = 0.28239$	$d = 0.9741$	0.97248	
175	$c = 0.3545$	$d = 1.01739$	0.97419	
185	$c = 0.4654$	$d = 1.12909$	0.97795

FIGURE 8: Stress-strain curves at different frequencies.

elastic modulus began to decrease with the number of cycles until the increase rate reached zero. Subsequently, as the dynamic stress amplitude continued to increase, the dynamic elastic modulus began to decrease with the number of cycles, and the decrease rate continued to increase.

3.4. Damping Ratio. The damping effect of soil on the dynamic load manifests the lag phenomenon of the strain in the hysteresis loop under cyclic loading, which is mainly caused by the internal friction effect of the relative sliding between particles. The damping ratio, λ , which is determined by the shape of the hysteresis loop, can reflect the ability of the soil to absorb vibration energy [35].

$$\lambda = \frac{1}{4\pi} \frac{A_0}{A_T}, \quad (5)$$

where A_0 represents the mechanical energy consumed by the soil during the loading and unloading periods and A_T

FIGURE 9: Curves of dynamic elastic modulus versus dynamic stress amplitude at different frequencies.

denotes the maximum elastic energy obtained by the soil in a cycle.

The λ - σ_d curves plotted using the damping ratio of the fifth cyclic loading under each loading level and the corresponding dynamic stress amplitude are depicted in Figure 11.

Figure 11 shows that the damping ratio of the mudstone sample increases with the increase in the dynamic stress amplitude. Under small dynamic stress amplitudes, the damping ratio increased linearly. Subsequently, with the increase in the dynamic stress amplitude, the increase rate of the damping ratio decreased and tended to be stable.

Under the same dynamic stress amplitude, the higher frequency leads to a faster loading rate. Thus, there is insufficient time for the mudstone sample to produce large deformation, thereby reducing the energy consumption. Therefore, the larger the final deformation, the higher the energy consumption, and the greater the damping ratio, and vice versa.

FIGURE 10: Dynamic elastic modulus versus cycle number curves under different dynamic stress amplitudes.

FIGURE 11: Damping ratio versus dynamic stress amplitude curves at different frequencies.

The variation in the damping ratio, λ , with cycle number N at 1 Hz is shown in Figure 12. Under a small dynamic stress amplitude, the dynamic damping ratio of the sample decreased with the increase in the number of cycles. When the dynamic stress amplitude increased, the rate of decrease of the dynamic damping ratio began to decrease with the cycle number until the decrease rate reached zero. Subsequently, as the dynamic stress amplitude continued to increase, the dynamic damping ratio

began to increase with the cycle number, and the rate of increase continued to increase.

4. Establishment of Mudstone Dynamic Constitutive Model

Based on the experimental results, an empirical dynamic constitutive model of mudstone that can describe the dynamic stress-strain expansion law of the sample in stable and damaged zones under cyclic loading was established.

Based on the hysteresis curve and Section 3.3, the dynamic elastic modulus was affected by cycle number N and loading frequency f . In this study, the relationship between the dynamic stress and dynamic strain in the stable and failure zones was obtained, as expressed in the following equation:

$$\varepsilon_d = \frac{\sigma_d}{E_d}. \quad (6)$$

To analyze the expression of the dynamic elastic modulus, a representative hysteresis curve was selected to fit the dynamic elastic modulus based on the test results. Figure 13 shows that the dynamic elastic modulus in the stable and failure zones changes with the cycle number under the loading frequencies of 0.5, 1, and 3 Hz.

The fitting results showed that the dynamic elastic modulus in the stable zone increased with the increase in the cycle number, whereas the increase in the amplitude was gradually reduced. The dynamic elastic modulus in the failure zone decreased linearly with the increase in the cycle number. An empirical relationship between the dynamic elastic modulus and cycle number was obtained from the

FIGURE 12: Damping ratio versus cycle number curves under different dynamic stress amplitudes.

fitting curve results. The stable and failure curves are expressed in the following equations, respectively.

$$E_d = A_1 \ln(N) + B_1 \quad (A_1 > 0), \quad (7)$$

$$E_d = A_2 N + B_2 \quad (A_2 < 0), \quad (8)$$

where A_1 , A_2 , B_1 , and B_2 denote the fitting parameters of the curve affected by the loading frequency.

To determine the functional relationship between the fitting parameters and loading frequency, the corresponding relationship curves were drawn, as depicted in Figure 14. As shown in Figure 14(a), fitting parameters A_1 and B_1 of the dynamic elastic modulus of the stable curve exhibited a linear relationship with the loading frequency, f , and the square of the correlation coefficient was above 0.9 (equations (9) and (10)).

$$A_1 = a_1 f + b_1, \quad (9)$$

$$B_1 = a_2 f + b_2, \quad (10)$$

where the values of fitting parameters a_1 , a_2 , b_1 , and b_2 are -0.8943 , 12.06 , 5.8381 , and 69.85 , respectively.

As depicted in Figure 14(b), fitting parameters A_2 and B_2 of the dynamic elastic modulus of the failure curve exhibited an exponential relationship with the loading frequency, f , and the square of the correlation coefficient was above 0.9 (equations (11) and (12)).

$$A_2 = l_1 \exp(m_1 f) + n_1, \quad (11)$$

$$B_2 = l_2 \exp(m_2 f) + n_2, \quad (12)$$

where the values of fitting parameters l_1 , l_2 , m_1 , m_2 , n_1 , and n_2 are -0.8686 , 19.12598 , -2.5022 , 0.24154 , -0.16752 , and 0 , respectively.

The aforementioned analysis can yield the relationship among the dynamic elastic modulus of the mudstone, cycle number, and load frequencies in the stable and failure zones.

The result of solving simultaneous equations (7), (9), and (10) is expressed in the following equation:

$$E_d = (a_1 f + b_1) \ln(N) + (a_2 f + b_2). \quad (13)$$

The result of solving simultaneous equations (8), (11), and (12) is expressed in the following equation:

$$E_d = [l_1 \exp(m_1 f) + n_1] N + [l_2 \exp(m_2 f) + n_2]. \quad (14)$$

Using equations (6), (13), and (14), the dynamic constitutive models of the stable and failure zones of the mudstone under cyclic loading can be obtained.

Stable zone:

$$\varepsilon_d = \frac{\sigma_d}{(a_1 f + b_1) \ln(N) + (a_2 f + b_2)}. \quad (15)$$

Failure zone:

$$\varepsilon_d = \frac{\sigma_d}{[l_1 \exp(m_1 f) + n_1] N + [l_2 \exp(m_2 f) + n_2]}. \quad (16)$$

In a constructed model, the unstable input parameters may result in the uncertainty of the model outputs. Vubac et al. [24] provided a robust and powerful modeling tool to quantify the influence of uncertain input parameters on uncertain model outputs. In this study, the

FIGURE 13: Dynamic elastic modulus versus cycle number curves in stable and failure zones. (a) 0.5 Hz. (b) 1 Hz. (c) 3 Hz.

sensitivity analysis method was used to consider the uncertainties. The results indicated that the dynamic stress amplitude, σ_d , was the most important parameter followed by the frequency, f , and cycle number, N . The other parameters related to the physical and mechanical properties of the samples exhibited insignificant influences on the axial strain.

5. Discussion

- (1) Based on the results of the conducted dynamic triaxial tests, the critical dynamic stress ranges of the sliding zone mudstone under 0.5, 1, and 3 Hz frequencies are

125–145, 235–255, and 245–285 kPa, respectively. The average critical dynamic stress of the mudstone in the sliding zone increases with the increase in frequency. This indicated that increasing the frequency can enhance the antidynamic ability of the sliding zone and improve the stability of landslides.

- (2) Based on the dynamic elastic modulus, a dynamic constitutive model was established in this study. The model can be employed to describe the dynamic stress-strain relationships of the samples under cyclic loading. Under a certain dynamic stress amplitude, the dynamic stress-strain relationship expressed by the model can be transformed into the relationship

FIGURE 14: Curves of fitting parameters of dynamic elastic modulus versus frequency. (a) Stable curve-fitting parameters. (b) Failure curve-fitting parameters.

between the number of cyclic vibrations and dynamic strain. When the dynamic stress is set as a variable, equation (15) can be transformed for studying the dynamic strength of the mudstone in the slip zone under a cyclic dynamic load. This model is suitable for a test case in which the axial dynamic load increases stepwise, instead of continuously increasing axial dynamic load.

- (3) The experimental study is based on a high-steep rock landslide with a weak interlayer in the Qinling-Daba mountain, and the results provide a basis for the dynamic study of landslides in this area. In this study, the dynamic characteristics test is conducted on the weak layer of rock landslide. The deformation characteristics of landslide weak interlayer under dynamic action are analyzed, and relevant conclusions are obtained. However, the case of the soft and hard interlayer contact surfaces is not involved in this study. More research is needed to conduct on the influence of dynamic load from the perspective of soft and hard interlayer contact surfaces and dynamic intermittent loading.

6. Conclusions

- (1) The dynamic stress amplitude and loading frequency presented a significant effect on the deformation characteristics of the mudstone samples in the sliding zone of the Shanyang landslide. The axial strain increased with the increase in the cycle number, and the rate of increase continuously increased. Increasing the dynamic stress amplitude and cycle number increased the elastic and plastic strains exponentially.

Additionally, the elastic strain was more sensitive to the increase in the dynamic stress amplitude compared to the plastic strain. As the loading frequency increased, the number of cycles required for the failure of the specimen increased, the strain decreased, and the strain growth rate decreased. Additionally, the influence of the loading frequency on the strain decreased with the increase in the loading frequency.

- (2) The dynamic elastic modulus decreased linearly with the increase in the dynamic stress amplitude, and as the frequency decreased, the linear decrease rate of the dynamic elastic modulus increased. The damping ratio increased with the increase in the dynamic stress amplitude. Under the same dynamic stress amplitude, as the loading frequency increased, the dynamic elastic modulus increased and the damping ratio decreased.
- (3) In the dynamic stress-strain relationship, the dynamic elastic modulus in the stable zone increased with the increase in the cycle number, whereas that in the failure zone decreased with the increase in the cycle number. The empirical model of the dynamic constitutive relationship with cycle number N and loading frequency f based on the dynamic elastic modulus could satisfactorily describe the dynamic stress-strain relationship of the samples in the stable and failure zones.

Data Availability

The experimental data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this study.

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