Influence of stress amplitude on the dynamic characteristics of phyllite samples under triaxial multi-stage cyclic loading

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Abstract: The generation of a rockslide in an earthquake event is strongly dependent on the dynamic characteristics of the rock materials constituting the rock slope. In this study, phyllite samples were extracted from the Donghekou landslide area of Qingchuan County. The landslide occurred during the 2008 Wenchuan earthquake and the samples were made to undergo multi-stage cyclic loading and unloading tests under triaxial compression conditions. The confining pressure during the tests was 10 MPa, the loading frequency was 2 Hz, the loading waveform was sine wave, and 60 loading cycles were carried out at each level of stress. From the dynamic axial stress–strain curves, the effect of stress amplitude on the hysteresis loop area, the dynamic elastic modulus, the dynamic damping ratio, and the damping coefficient of the phyllite samples was analyzed. The results are as follows. (1) The strain–stress hysteresis loop area experienced a rapid increase as the stress amplitude exceeded a certain value, indicating that the rock samples have entered an accelerating crack propagation stage under high level of cyclic loading. (2) As the stress amplitude increases, the dynamic elastic modulus, the dynamic damping ratio, and the damping coefficient of the rock sample followed a similar two-phase evolution law. There was a rapid reduction in the three parameters relative to the initial value in Phase I. Moreover, there was a minor change in Phase II. (3) The effect of the number of loading cycles on dynamic elastic modulus and damping parameters was much more obvious under the lower levels of cyclic loading than under the higher levels.

Keywords. cyclic loading; phyllite; stress amplitude; dynamic elastic modulus; damping ratio; damping coefficient

1. Introduction
Natural rock mass is subjected to both static loads and to dynamic loads such as earthquakes. It is a commonly seen phenomenon that rock mass engineering is damaged under an earthquake; however, dynamic properties of rock mass are still not completely understood. In the past few years, a number of experimental studies have been performed to understand certain dynamic mechanical behaviors of different types of rock mass. These studies have noted that dynamic properties such as dynamic elastic modulus, dynamic Poisson ratio, and damping ratio of rock mass changes with different control variables under cyclic loads [1]. Notable among these studies is the work of Cai et al.[2] who performed experimental tests and theoretical analysis on deformation characteristics of rock materials.
under cyclic loading. Xie et al.[3] studied the internal relationship between energy dissipation and release and the rock strength during rock deformation and failure. He et al. [4] performed multi-stage cyclic loading tests on sandstone, conglomerate and conglomerate. The results show that the higher the stress level, the higher the dynamic elastic modulus. The larger the water content and stress amplitude, the smaller the dynamic elastic modulus and the larger the dissipated energy. Ge et al.[5] studied the fatigue failure deformation of sandstone, marble, and granite through uniaxial compression tests. Moreover, an analysis of the development law of irreversible deformation during fatigue failure of rock under periodic load was conducted by the authors. Liu et al. [6] studied the deformation and damping parameters of rock under cyclic loading. Moreover, they discussed the influence of cyclic loading cycles and dynamic stress amplitude on dynamic elastic modulus, dynamic Poisson’s ratio, damping ratio, and damping factor of fine sandstone. Through experimental studies, Guo et al.[7] revealed that the ratio of initial and cyclic axial strain of salt rock increased with the increase of the maximum and average stress values. The study, however, noted that the total number of cycles significantly decreased during fatigue failure. Shalev et al.[8] studied the effect of stress amplitude on volumetric strain and bulk modulus during cyclic loading and unloading test of sandstone. Ma et al. [9] reported that the upper and lower limits of cyclic load stress had considerable influence on deformation evolution and damage development of salt rock.

From the literature, most of the previous researches primarily focused on fatigue deformation, failure characteristics, and the damping characteristics of rock mass under uniaxial compression tests, and only limited research considered the effect of confining pressure. In this study, a triaxial compression test was performed on phyllite samples to explore its dynamic properties such as dynamic stress–strain behaviors, dynamic elastic modulus, damping ratio, and damping coefficient under multi-stage cyclic condition. In the following analysis, an attempt was made to determine the influence of stress amplitude on these dynamic properties.

2. Experimental preparation

2.1 Sample preparation

Rock samples were collected from the Donghekou landslide area of Qingchuan County, Guangyuan City, Sichuan Province. The sliding body was primarily composed of Sinian Yuanji Formation limestone and dolomite, Cambrian Qiujiahe Formation carbonaceous slate, and Youfang Formation sericite phyllite. The phyllite samples used for this study is presented in Figure 1. Three standard cylindrical rock samples were prepared according to the requirements of sample preparation outlined in the standard Engineering Rock Mass Test Methods (GB/T 50266-2013). The standard size of the sample is Φ50×100 mm, and the average density of phyllite samples is 3.16 g/cm³. The samples were sealed and isolated before and after preparation to maintain the natural state of the samples as much as possible.

![Figure 1. Phyllite test samples](image1)

![Figure 2. MTS rock mechanics test system](image2)
2.2 Experimental equipment
The MTS815 flex test GT dynamic test system was adopted in this study, as shown in Figure 2. The test system is composed of computers and an automated digitally automatic control system. It can collect load, stress, displace, and stress variables simultaneously during the test. Moreover, it can draw stress–strain and load–displacement curves. Moreover, it can draw stress–strain and load–displacement curves. The axial load range is 0–4600 kN and the axial displacement range is from −50 to 50 mm. The measuring range of the annular deformation extensometer is −2.5 t 12.5 mm and −4.0 to 4.0 mm. The maximum confining and osmotic pressure is 140 MPa, and the maximum osmotic pressure difference is 30 MPa, and the vibration frequency is >5 Hz. The vibration waveform can be a sinusoidal, triangular, square, oblique, or a random wave. The vibration phase difference can be set arbitrarily from 0 to 2. The vibration loading control mode is axial, the confining and seepage pressures, or any combination of waveform, frequency, and phase of the above three loading control modes.

The power amplifier amplifies a given signal sent from the microprocessor signal generator which is then inputted to the host for vibration. The vibration signal is transferred from the sensor to the dynamic strain amplifier. The data is then fed back by the data acquisition board and stored in the computer for onward sorting and analysis.

2.3 Experimental process
A multi-stage cyclic loading and unloading test was performed on the three rock samples under the triaxial compression condition. Cyclic loading and unloading were accomplished by inputting a sine wave with a vibration frequency of 2.0 Hz. The cyclic number at each stress level was 60. The test loading condition is shown in Table 1, and the main experimental process is as follows:

1) Pre-test preparation: The cylindrical sample was placed between the two pads, the samples are then wrapped with a thermoplastic tube, after which the prepared sample was loaded on the loading base.

2) Cyclic loading: The samples were loaded under a 10 MPa confining pressure with a sine wave of 2 Hz frequency in the axial direction and a loading speed controlled by displacement at 0.1 mm/min. As can be seen in Figure 3, before each level of cyclic loading, a ramp loading was performed until the axial stress increased to a designed maximum stress. This was followed by 60 cycles of loading and unloading after which the next loading stage was performed until the rock sample was destroyed. The test data were simultaneously recorded and the complete loading curve of axial stress versus time outputted. A plot of the axial stress loading process curve for the phyllite sample B-1 is shown in Figure 3.

| Samples | Confining pressure (MPa) | Lower limit stress (MPa) | Loading stages | Maximum Stress (MPa) | Stress Amplitude (MPa) | Frequency (Hz) |
|---------|--------------------------|--------------------------|----------------|----------------------|-----------------------|----------------|
| B-1     | 10                       | 60                       | 1              | 75                   | 15                    | 2.0            |
|         |                          |                          | 2              | 85                   | 25                    |                |
|         |                          |                          | 3              | 95                   | 35                    |                |
|         |                          |                          | 4              | 105                  | 45                    |                |
|         |                          |                          | 1              | 75                   | 15                    |                |
|         |                          |                          | 2              | 85                   | 25                    |                |
|         |                          |                          | 3              | 95                   | 35                    |                |
| B-2     | 10                       | 60                       | 4              | 105                  | 45                    | 2.0            |
|         |                          |                          | 5              | 115                  | 55                    |                |
|         |                          |                          | 6              | 125                  | 65                    |                |
|         |                          |                          | 7              | 135                  | 75                    |                |
|         |                          |                          | 1              | 75                   | 15                    |                |
|         |                          |                          | 2              | 85                   | 25                    |                |
| Phyllite|                          |                          | 3              | 95                   | 35                    | 2.0            |
|         |                          |                          | 4              | 105                  | 45                    |                |
| B-3     | 10                       | 60                       | 5              | 115                  | 55                    |                |

2.4 Calculation principle of rock dynamic parameters

As a typical non-ideal elastomer, certain flaws such as pores and cracks are randomly distributed in the rock mass [10]. During multi-stage cyclic loading and unloading, the pre-existing pores and cracks close and expand under external loads. This results in a non-linear dynamic stress–strain curve with the occurrence of a hysteresis loop in each cycle.

Figure 4 shows that the unloading curve is lower than the loading curve. The hysteresis loop reflects the energy dissipated during the loading and unloading of a single cycle. According to the energy theory, the dynamic elastic modulus of a rock is the reflection of its dynamic elastic property under dynamic loading, and its value reflects the elastic bearing performance of the rock. The rock damping ratio represents the ratio of the total energy consumed by a rock during a single loading period to its elastic strain energy. The relationship between the damping ratio $\lambda$, damping coefficient $C(\text{kN} \cdot \text{s} \cdot \text{mm}^{-1})$, and the dynamic elastic modulus $E_d (\text{MPa})$ is given by [6]:

$$\lambda = \frac{A_R}{4\pi A_s} \quad (1)$$

$$C = \frac{A_R}{\pi \chi^2 \omega} \quad (2)$$

$$E_d = \frac{\sigma_{d_{\text{max}}} - \sigma_{d_{\text{min}}}}{\varepsilon_{d_{\text{max}}} - \varepsilon_{d_{\text{min}}}} \quad (3)$$

where

$\sigma_{d_{\text{max}}}$ is the maximum dynamic stress of one dynamic stress–strain hysteresis loop.

$\sigma_{d_{\text{min}}}$ is the minimum dynamic stress of one dynamic stress–strain hysteresis loop.

$\varepsilon_{d_{\text{max}}}$ and $\varepsilon_{d_{\text{min}}}$ are the maximum and minimum strains of hysteresis loop, respectively.

$\chi$ is the response displacement amplitude (mm) given by [11].

$\omega$ is the loading frequency (rad/s).

$A_R$ is the area ABCD in Figure 4 of one hysteresis loop (kN·mm).

$A_s$ is the area of the triangle AEF in Figure 4 (kN·mm) and the factor $4A_s$ is the maximum elastic...
3. Experimental results

3.1. Axial stress–strain curve under cyclic loading

In this section, a comparison of the hysteresis loops of the dynamic stress–strain curve for each rock sample under different stress amplitudes is presented. In each loading stage, the first, 30th, and 60th cycle were selected and the hysteresis loops outputted as shown in Figure 5 (a)–(c). From the figure, it is observed that there is an increase of stress amplitude of hysteretic loops at different stress levels. The loop is generally observed to increase in size, indicating a significant change in rock structure. However, at the same stress level, the hysteresis loop changed slightly in different cycles.

Figure 5(d) shows the relationship between the average area of the hysteresis loop in one loading stage and stress amplitude. From the figure, the area of the hysteresis loop exhibited a monotonous increasing trend as the stress amplitude increases with increasing speed. When the stress amplitude increased from 15 to 45, 55 and 75 MPa, the area of the hysteresis loop of the B-1 sample increased by 7.5, 9.5, and 14.2 times, respectively, when compared with the first stage.

From the thermodynamic point of view, energy dissipation is a one-way and irreversible process, while energy release is bidirectional and reversible under certain conditions [12]. Under cyclic loading, the external load will both increase the elastic deformation energy of the rock sample and dissipate a part of the energy in other forms (e.g., crack development). The dissipated energy in the loading process was not released from the rock sample in the subsequent unloading process. During the cyclic loading, the cracks expanded in the phyllite sample with an increase in the stress amplitude. This resulted in an increase in the energy dissipation macroscopically and an increase of the area of the hysteresis loop in a high level of stress amplitude.

![Graphs showing stress-strain curves for different stress amplitudes](image)

(a) Sample B-1  
(b) Sample B-2

![Graph showing hysteresis loop areas](image)

(c) Sample B-3  
(d) Hysteresis loop areas of three samples

Figure 5. Hysteresis loops of phyllite samples under different levels of stress amplitude.
3.2 Dynamic elastic modulus analysis under cyclic loading

Figure 6(a) shows the variation of dynamic elastic modulus with stress amplitude under the 1st, 15th, 30th, 45th, and 60th cyclic loading for Sample B-2. Under the same number of cyclic loading, the dynamic elastic modulus was observed to initially decrease rapidly with an increase in stress amplitude. However, when the stress amplitude exceeded a certain value, the decreasing speed slowed down. The average dynamic elastic modulus at each stress level was calculated and its relationship with stress amplitude are presented in Figure 6(b). Consequently, two-phase evolution law of dynamic elastic modulus with stress amplitude was suggested with the cut-off stress amplitude of 35 MPa. In Phase I, the dynamic elastic modulus decreased by 3.5% compared to the initial state when the stress amplitude was <35 MPa. For Phase II, only 0.95% of reduction in elastic modulus occurred when the stress amplitude exceeded 35 MPa.

The relationships between dynamic elastic modulus and cycle number for Sample B-2 are presented in Figure 7. From the figure, when the stress amplitude was low (i.e., 15 MPa), the dynamic elastic modulus increased gradually as the cycle number increased up to 30 cycles, and then stabilized until the loading stage ended. The closure of pre-existed flaws (e.g., pores and cracks) in the rock sample may be responsible for the increase of the elastic modulus at the beginning of a loading stage. This phenomenon was not observed when the stress amplitude was 45 MPa.

![Figure 6. Relationships between dynamic elastic modulus and stress amplitude for Sample B-2](image)

![Figure 7. Relationships between dynamic elastic modulus and cycle number for Sample B-2](image)

3.3 Dynamic Damping Parameter Analysis under Cyclic Load

Figure 8(a) shows the variation of dynamic damping ratio with stress amplitude under the 1st, 15th, 30th, 45th, and 60th cyclic loading for Sample B-2. Under the same number of cyclic loading, the dynamic damping ratio decreased as the stress amplitude increased, with a maximum reduction of 55% compared to the initial state under the 30th cyclic loading and a minimum reduction of 36% under the 1st cyclic loading. The average dynamic damping ratio at each stress level was calculated...
and its relationship with stress amplitude is shown in Figure 9(a). When compared with Figure 6(b), a similar two-phase evolution law was observed for damping ratio as the stress amplitude increased. A decrease of 39.8% in the damping ratio compared to the initial state when the stress amplitude was <35 MPa was observed for Phase I; however, in Phase II, 8.2% of reduction in damping ratio occurred when the stress amplitude exceeded 35 MPa.

Figure 10(a) shows the relationships between dynamic damping ratio and loading cycle number under different levels of stress amplitude for Sample B-2. From the figure, it can be seen that when the stress amplitude was as low as 15 MPa, the dynamic damping ratio was observed to gradually increase as the cycle number increased up to 30 cycles. The increment then stabilized until the loading stage ended. Under higher levels of cyclic loading, the influence of cycle number on damping ratio was relatively weak.

The decrease in damping ratio with increasing stress amplitude can be attributed to the cracks in the rock that developed more slowly during each cycle, and the damage to the specimens because of each cycle gradually decreasing. The reason why the increase of damping ratio with increase in cycle number may be that, under low stress amplitude, the damping ratio of the samples increased with the number of cycles. Note that the damping ratio is related to crack propagation and initiation in rock. The more fragmented the rock interior, the more plastic deformation will occur and the greater the damping ratio will be.

A similar results trend for damping ratio discussed above can be obtained for the damping coefficient on the basis of conditions for Figure 8(b), Figure 9(b), and Figure 10(b). The percentage reductions of these two damping parameters relative to the initial value of Sample B-2 are summarized in Table 2 as the stress amplitude increased.

![Figure 8](image1.png)  
**Figure 8.** Relationship between dynamic damping parameters and stress amplitude for Sample B-2

![Figure 9](image2.png)  
**Figure 9.** Relationship between dynamic damping parameters and stress amplitude for Sample B-2
Figure 10. Relationship between dynamic damping parameters and cycle number for Sample B-2

### Table 2. The reduction of dynamic damping ratio and damping coefficient under different levels of stress amplitude.

| Phase | Cycle Numbers (N) | $\sigma_E$ (MPa) | 1   | 15  | 30  | 45  | 60  | Average |
|-------|-------------------|------------------|-----|-----|-----|-----|-----|---------|
|       |                   | ($\lambda$) (%)  | ($\lambda$) (%) | ($C$) (%) | ($\lambda$) (%) | ($C$) (%) | ($\lambda$) (%) | ($C$) (%) |
| I     | 15                | 25               | 21  | 30  | 35  | 32  | 34  | 28  | 30  | 30  | 32  | 39.8 | 41.4 |
|       | 25                | 30               | 31  | 42  | 43  | 45  | 47  | 40  | 42  | 42  | 44  |
| II    | 45                | 55               | 32  | 34  | 46  | 48  | 50  | 53  | 47  | 46  | 49  |
|       | 55                | 65               | 34  | 36  | 48  | 50  | 52  | 54  | 47  | 49  | 51  | 48  | 50.6 |
|       | 75                | 75               | 36  | 38  | 50  | 53  | 55  | 57  | 49  | 51  | 50  | 54  |

$\sigma_E$ is stress amplitude  
$\lambda$ is damping ratio  
$C$ is damping coefficient

### 4. Conclusions

In this study, multi-stage cyclic loading and unloading tests were performed on phyllite samples under triaxial compression. Based on the dynamic axial stress–strain curves, the effect of stress amplitude on the hysteresis loop, the dynamic elastic modulus, the dynamic damping ratio, and the damping coefficient of phyllite samples were analyzed. The following conclusions have been drawn.

1. An insignificant change in the stress–strain hysteresis loop area was observed at low stress amplitude that increases significantly as the stress amplitude exceeds a certain value. This indicates that the rock samples have entered an accelerating crack propagation stage because of the high level of cyclic loading. It resulted in the dissipation of a large amount of energy.

2. As the stress amplitude increased, the dynamic elastic modulus, the dynamic damping ratio, and the damping coefficient of the rock sample follow a similar two-phase evolution law. In Phase I, a rapid reduction in the values of the three parameters compared to the initial value was observed as the stress amplitude increased. In Phase II, an insignificant change occurred.

3. Under the same level of cyclic loading, the dynamic elastic modulus, the dynamic damping ratio and the damping coefficient increased as the number of cycles increased during the early stage of...
dynamic loading. It then either stabilized or decreased in the later stage. This phenomenon was not observed under high levels of loading.

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