Influence of Moisture Content and Stress Cyclic Loading Amplitude on the Dynamic Characteristics of Sandstone

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ABSTRACT

Ever since the Three Gorges Project started operation, based on the requirements of reservoir operation standard, the water level in the reservoir has been fluctuating between 145m-175m. On the one hand, the significant change in the water level has a cyclic loading and unloading effect on the slope; on the other hand, part of the slope undergoes wetting-drying cyclic process, and the moisture content of the slope has been fluctuating. In this paper, an experimental study has been done to investigate the effects of the moisture content and the stress amplitudes on the sandstone's stress-strain hysteresis curve, dynamic elastic modulus, damping ratio, damping coefficient and other dynamic parameters. The results showed that: (1) under cyclic loading and unloading, the shape of the stress-strain hysteresis loop was not only dependent on the rock properties, but also closely dependent on the moisture content and the stress amplitude. The smaller the moisture content and the higher the stress amplitudes are, the slender the hysteresis loops. (2) As the moisture content of the rock samples increased, the sandstone damping coefficient, the damping ratio, and the dynamic elastic modulus decreased. The air dry samples exhibited higher dynamic parameters than the rock specimens with the natural moisture content. Similarly, the rock specimens with the natural moisture content had higher values of dynamic parameters than the saturated ones. (3) With the increase of the cyclic loading stress amplitude: the sandstone damping ratio and the damping coefficient decreased and showed a power function $\lambda = af^{b}$ (a, b are fitting parameters, $a > 0$, $b<0$).The damping ratio and the damping coefficient were reduced by 188% and 49% respectively. The dynamic elastic modulus increased linearly. In contrast, the stress amplitude had a significant impact on the damping ratio and the dynamic elastic modulus. The research results provide a better basis for the evaluation of the dynamic characteristics of the bank slope.

KEYWORDS: cyclic loading, stress amplitude, moisture content, damping radio, damping coefficient, and dynamic elastic modulus.

INTRODUCTION

In engineering, rocks need to withstand not only static loading, but also dynamic loading such as earthquake, cyclic loading, blasting and so on. Since the Three Gorges project started the operation, based on the requirements of reservoir operation standard, the water level in the reservoir area has been fluctuating between 145m-175m. On the one hand, the significant change in the water level has a cyclic loading and unloading effect on the slope. On the other hand, part of the slope undergoes cyclic wetting and drying process for a long period of time; the degree of moisture content has been fluctuating. And it might affect the dynamic properties and characteristics of the slope. Analysis and determination of the dynamic response of the rocks are important task of the structural design and safety assessment. Selections and computations of the dynamic parameters may or may not simulate the real engineering problems. Previous studies have shown that, under cyclic loading and different control variables or factors, structural materials could exhibit different mechanical performances [1]. Many factors will affect the dynamic characteristics of the rock mass, including moisture content, internal defects of the rock sample, loading stress, frequency and amplitude. Previously, researchers [2] and [3] comprehensively studied the effect of the moisture content, and the wetting-drying process on the sandstone's strength and the p-wave's velocity. The nonlinear and non-monotonic relationships between the p-wave velocity and the moisture content have been understood. In earlier experimental study , the authors [4] and [5] studied the effect of frequency (cyclic loading and unloading) , number of cycles, and stress amplitudes on the rock's dynamic and deformation parameters. It was found that, as the stress amplitude increased the dynamic elastic modulus and Poisson's Ratio of the sandstone increased; and their trend followed parabolic and linear function respectively. Both the damping ratio and the damping coefficient decreased and the trend showed power function. , The authors [6] and [7] studied the response of the dynamic elastic modulus on the stress amplitude and stress level. The finding showed the variation of the dynamic elastic modulus and dissipation energy with the stress amplitude, stress level and moisture content. The research revealed that, the higher the moisture content and stress amplitude are, the smaller the dynamic elastic modulus and the higher the dissipation energy. Researchers have done plenty of studies based on different perspectives, considering different rock types, moisture content, frequency, number of cycles (loading and unloading) and other factors, and have made many interesting findings in the study of the rock dynamic characteristics [8] and [9].

In practice, the moisture content and the applied loading amplitudes are not specific values. A few studies considered the effects of stress amplitude and moisture content on the dynamic properties of the rock. Based on this, an attempt has been done to investigate the effects of different moisture content and stress amplitude on the sandstone's stress-strain hysteresis curve, dynamic elastic modulus, damping ratio and damping coefficient and other effects of dynamic parameters. Experimental study was carried out on the Sandstone specimens by considering different moisture content and cyclic loading. The research results can provide a better basis for the evaluation and analysis of the dynamic characteristics of the bank slope.

MATERIALS AND METHODS

In this experimental study, the sandstone samples brought from the Three Gorges Reservoir area were used and cylindrical specimens (50 mm, diameter by 100 mm, height) were prepared. Before the main testing program, high quality rock specimens were chosen based on the P-wave velocity and the rebound value [10]. The mechanical experiment has been conducted by using RMT-150C, rock mechanism testing device. The axial compressive strength of the tested sandstone sample was about 55MPa. To study the effects of the change in moisture content on the sandstone's dynamic properties, the selected specimens were further categorized into three different groups. Each group simulates the three different conditions of the rock specimens (i.e., air-dry state, natural water content state and saturated water content state). In addition, each group consisted of three rock specimens. The employed rock specimens are shown in Figure 1.

Figure 1: Rock Specimens used for the experiment

According to " Specifications for rock tests in water conservancy and hydroelectric engineering ", The first group of the rock specimens were oven dried for about 24 hours at 105~110℃, and then transferred and placed in a drying chamber. Consequently, the specimens were cooled at room temperature and weighed. This step was repeated until the difference in weight between two successive weighing became no more than 0.1% of the previous weighing; it was used to simulate the air-dry condition. Vacuum pumping saturation technique has been introduced for the second group of the rock specimens to simulate the saturated water content state. However, the third group of the rock samples was sealed in plastic wraps to avoid loss in moisture content or to keep the natural moisture content. The cyclic loading frequency and the lower limits of the cyclic loading stress were 0.1Hz and 5MPa respectively. In rock engineering dynamic properties are determined based on elasticity. Therefore in this study, the employed maximum upper limits of the stress amplitude were relatively small. The main introduced stress amplitudes were 15,20,25,30,35, and 40MPa. Each stress levels had ten cycles, the loading and unloading were done by using stress-control method, and the applied loading waveform was sine wave. After the last stage of the loading, the tested samples were directly loaded to failure to analyze the effects of loading and unloading on the samples' strength.

PRINCIPLES USED TO DETERMINE THE DYNAMIC PROPERTIES OF THE ROCK

Since the rock medium is not perfectly elastic medium, during the process of cyclic loading and unloading : the loading and unloading curve shows a non-linear distribution and the unloading curve is lower than the loading curve. The hysteresis loop established by the dynamic stress - strain curve is shown in Figure 1. The area of the hysteresis loop reflects the energy dissipated during the process of the loading and the unloading stages. Damping ratio λ , damping coefficient C(kN·s·mm^{-1}) , the dynamic elastic modulus E_d(MPa), and the dynamic Poisson's ratio are defined as follows.

$$\lambda = A_R / 4\pi A_s \tag{1}$$

$$C = A_R / \pi X^2 \omega \tag{2}$$

$$E_d = (\sigma_{d\max} - \sigma_{d\min})/(\varepsilon_{d\max} - \varepsilon_{d\min}) \tag{3}$$

where $\sigma_{d\max}$ and $\sigma_{d\min}$ are the maximum and the minimum stress level of the dynamic stress-strain hysteresis loop ; $\varepsilon_{d\max}$ and $\varepsilon_{d\min}$ stands for the maximum and the minimum strain of the dynamic stress-strain hysteresis loop respectively; A_R(kN·mm) represents the area of the hysteresis loop, ABCD; similarly A_S(kN·mm) represents the area of the triangle, AEF, 4A_S represents the maximum elastic strain energy of the rock during a cyclic period; X(mm) represents the response amplitude; and ω stands for the circular frequency of the loading and the unloading stages (rad/s).

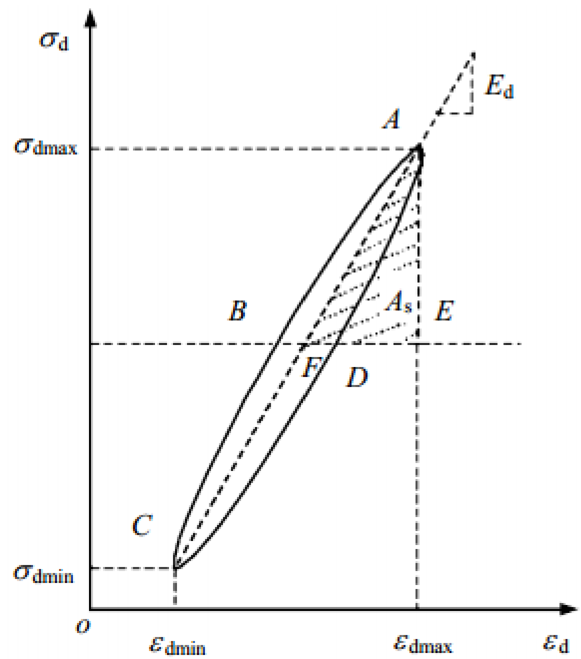
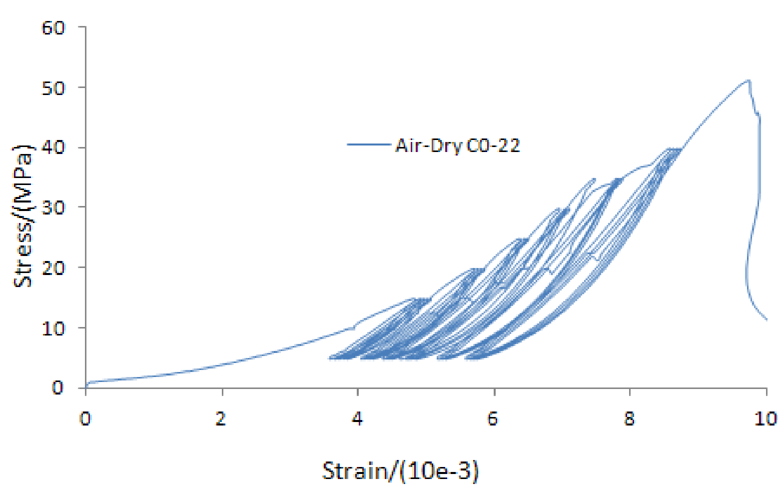


Figure 2: Hysteresis loop of the dynamic stress and strain curve

THE CHARACTERISTICS ANALYSIS OF TYPICAL SANDSTONE STRESS-STRAIN CURVE

Under different moisture content, the sandstone dynamic stress-strain curve is slightly different. From each group (saturated, natural moisture content and air-dry condition), one typical sample has been chosen, analyzed and the corresponding stress strain curves are presented in Figure 3.



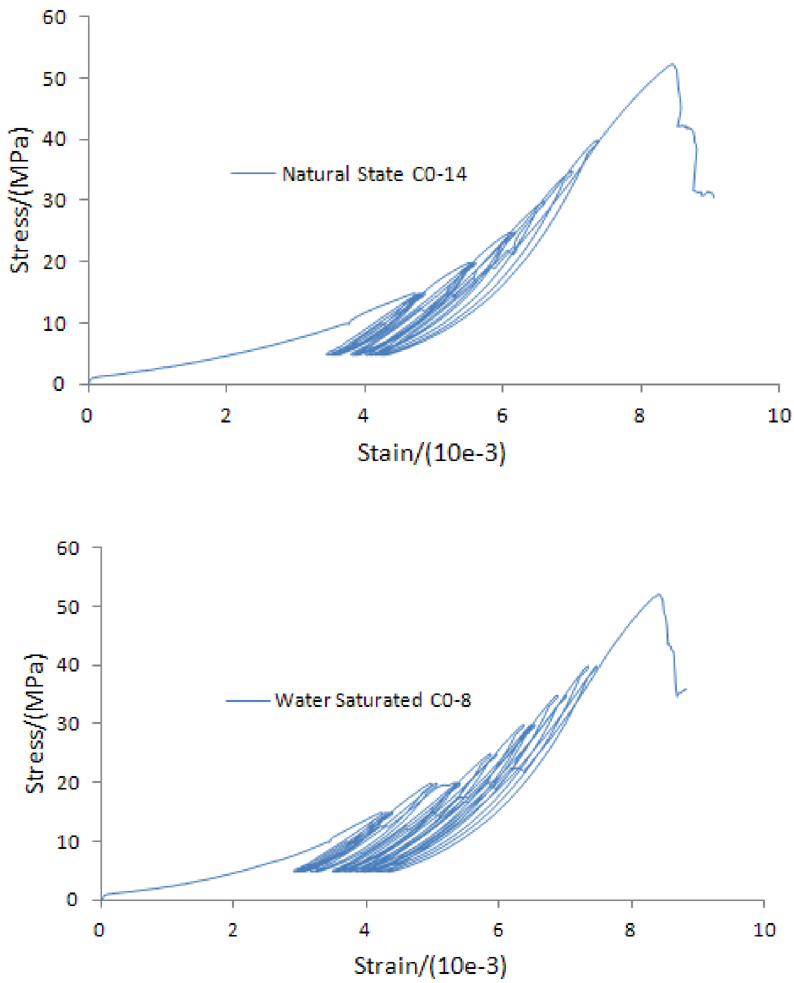


Figure 3: Typical dynamic stress-strain curve

Under different cyclic loading amplitude and frequency, the stress and strain curves have basically the same general trend (Figure 3). During each stage of the cyclic loading, the dynamic stress-strain curves were intersecting the parallel distribution. As the number of cycles increased, the dynamic stress-strain hysteresis loop moved towards in the direction of the strain increase. Following the increment in stress amplitude, the hysteresis loop area was gradually increased and the irreversible deformation of the rock samples was increased. After careful observation, one can understand the variations in the hysteresis loops under different moisture content. The smaller the moisture content, the hysteresis loop was obviously slender, the higher the moisture content, the hysteresis loops was even wider, and the corresponding strain at the failure point was significant. The strain at the failure under different moisture content (Table 1) has been computed and presented in Figure 4. The abscissa in Figure 4 represents different moisture content, in which 0.2 represents air-dry state, 0.6 represents natural state, 1.0 represents saturated state, and the Y axis represents the rock strain at failure.

Table 1: The moisture content of different rock samples

Moisture state	Rock No.	Moisture content
Air-dry	C0-17	–
	C0-22	–
	C0-25	–
Natural state	C0-11	0. 17%
	C0-14	0. 17%
	C0-15	0. 14%
Water saturated	C0-4	0. 37%
	C0-5	0. 33%
	C0-8	0. 44%

As it can be seen from Figure 4, the axial strain of the rock specimens at the failure was decreasing slightly while the moisture content increased. In order to investigate the effects of the stress amplitude and the moisture content on the sandstone's deformation characteristics, typical sandstone was chosen from each moisture content category. For the sake of comparative study the stress levels have been selected at the middle cycle. The hysteresis loops are partly overlapped at different cyclic stress amplitudes. In order to understand the change in the hysteresis loops easily, it was separately presented along the X axis as shown in Figure 5.

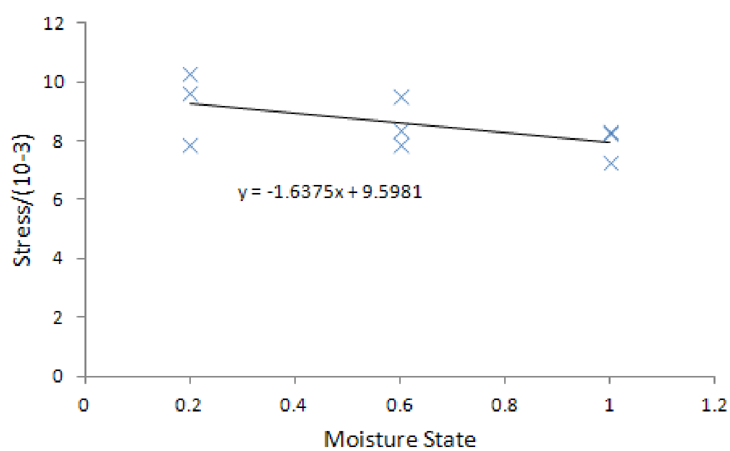


Figure 4: The strain of the rock specimens at failure under different moisture state

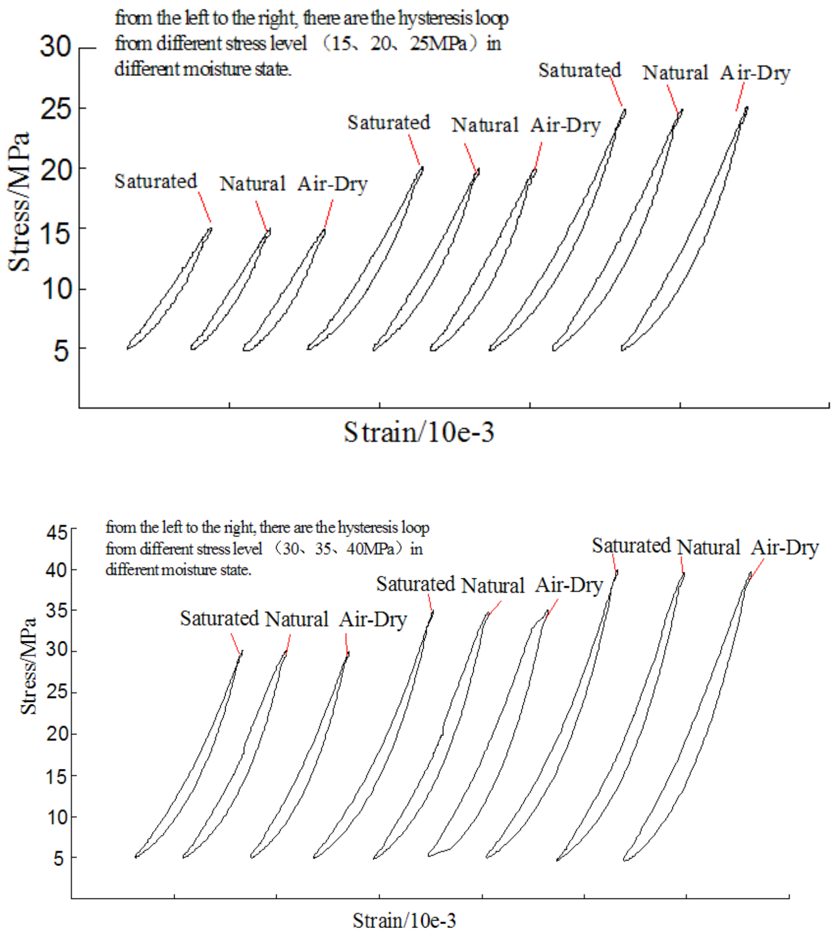


Figure 5: The hysteresis loops under different moisture states and stress amplitudes

The shapes of the dynamic stress-strain loops under cyclic loading were generally divided into crescent, eggplant, oval and so on. Other forms of the hysteresis loops have been identified by many researchers for different types of rocks under cyclic loading.

Figure 3-5 clearly indicated that, the hysteresis loops obtained from the experimental study exhibited an eggplant shape primarily, and the shape of upper part was leafy, which shows that, during the loading and unloading process, the sandstone elastic response was quick. While the shapes of the hysteresis loops were long eggplant, it became wider and wider as the moisture content reduced. When the stress amplitude increased the value of the trend became very noticeable. To examine the change in the hysteresis loop of the sandstone precisely, a total of 9 rock specimens with three different moisture conditions were used and the area of the 5th loop at each level have been computed (Figure 6).

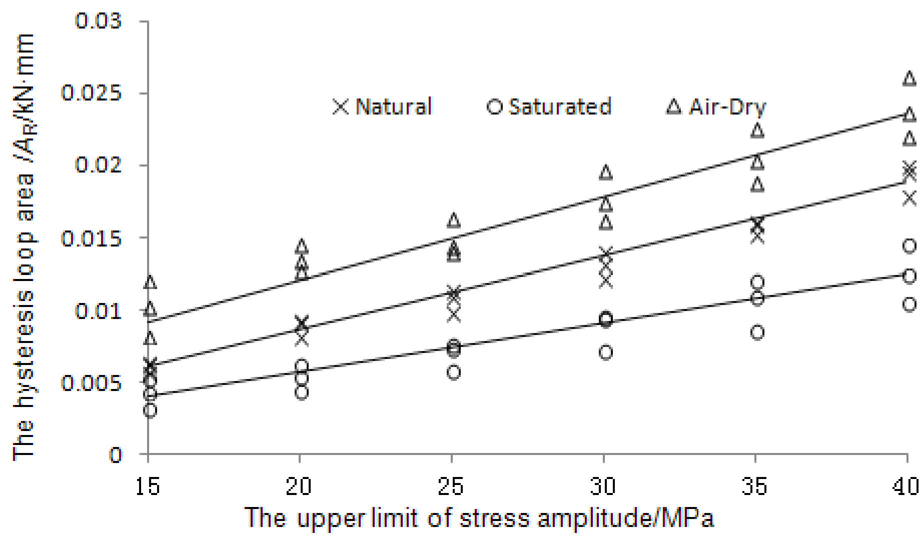


Figure 6: The area of typical hysteresis loop

From Figure 6 it can be seen that, air-dry specimens exhibited higher hysteresis loop area than specimens with natural moisture content at each stress amplitudes. Moreover, the specimens with the natural moisture content had larger area of the hysteresis loops than the saturated ones. Figure 4 illustrates the linear relationship between the stress amplitudes and the hysteresis loop area. Typically, as shown in Figure 6, when the stress amplitude varied between 5-15MPa, the hysteresis loop area increased from 3.5×10^{-3}kN·mm (saturation) to 9.5×10^{-3}kN·mm (air-dry), the increased amplitude was 6.0×10^{-3}kN·mm. Likewise when the stress amplitude was 5-30MPa, the hysteresis loop area increased from 8.0×10^{-3}kN·mm (saturation) to 18.5×10^{-3}kN·mm (air-dry), the increased amplitude was 10.5×10^{-3}kN·mm. The hysteresis loop area increased from 11.0×10^{-3}kN·mm (saturation) to 24.0×10^{-3}kN·mm (air-dry) while the stress amplitude varied between 5 to 40MPa , the increased amplitude was 13.0×10^{-3}kN·mm. It can be noticed that, the higher the stress amplitude range is, the higher the difference in the hysteresis loop area , and the morphological differences of the hysteresis loop are significantly considerable..

ANALYSIS OF THE DYNAMIC PARAMETERS FOR THE SANDSTONE SPECIMENS

One can determine the damping ratio, the damping coefficient, and the dynamic elastic modulus by using equation (1), (2) and (3). During the computation the 5th loop has been chosen at each stress level.

Analysis of the damping ratio and the damping coefficient for the sandstone

The change in the damping ratio and the damping coefficient for the rock specimens (9 rock samples with three different moisture states) are shown in the following Figures.

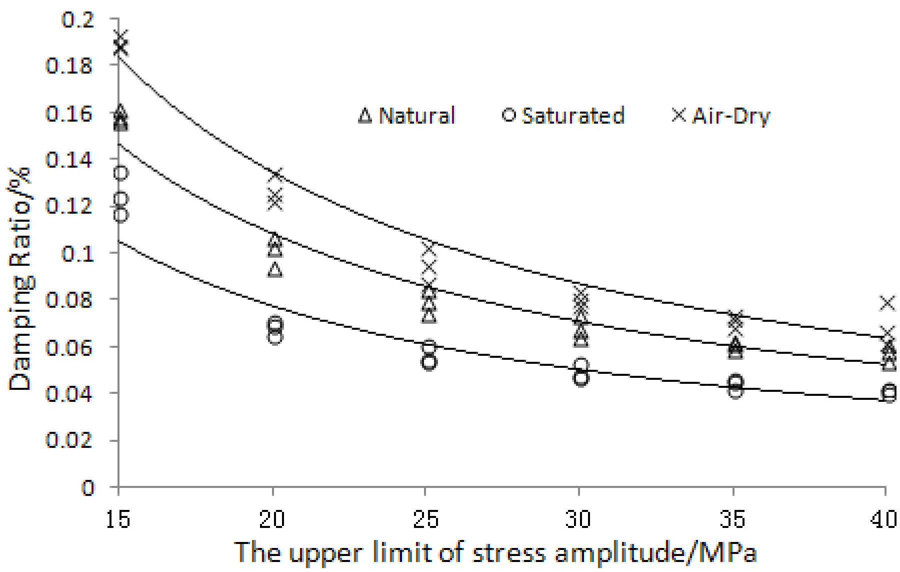


Figure 7: damping ratio vs. stress amplitude

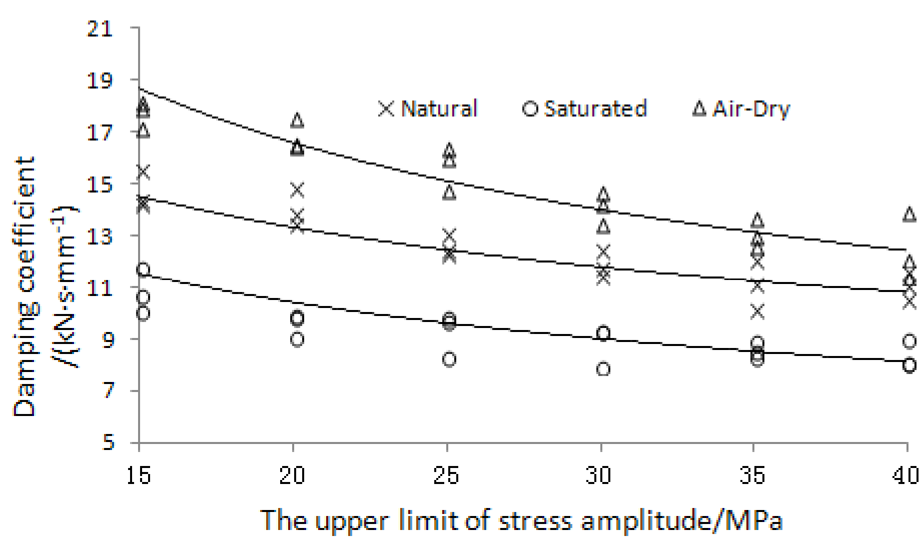


Figure 8: damping coefficient vs. stress amplitude

Figure 7 describes the relationship between the damping ratio and the stress amplitude follows the power function distribution $\lambda = af^{b}$ (a *and* b are fitting parameters, $a > 0$，b<0). $\lambda \; a \; f^{b}$ The damping ratio decreased sharply under low stress amplitude. However, as the stress amplitude increased, the rate of reduction has been dropped and became stable. The amplitude was reduced by 188%. The damping ratios of the air-dry samples were a little bit higher than the natural ones, and the natural ones were obviously higher than the saturated ones.

As it can be seen from Figure 8 while the stress amplitude increased, the damping coefficient of the sandstone's decreased and followed the power function distribution. Compared to the damping ratio, the reduction in the amplitude was relatively small, and it was about 49%. The damping coefficients of the air-dry samples were a little bit higher than the natural ones, and the natural ones were obviously higher than the saturated ones.

Analysis of the dynamic elastic modulus

One can calculate the dynamic elastic modulus by using Equation (3), as shown in Figure 9.

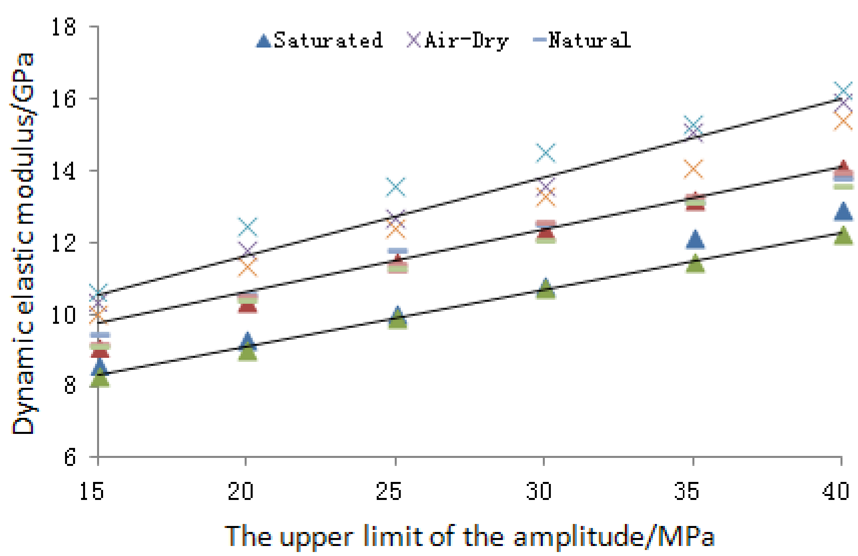


Figure 9: Dynamic elastic modulus vs. Stress amplitude

While the stress amplitude increased, the dynamic elastic modulus of the sandstone increased linearly (Figure 9). Due to the difference in moisture content, the dynamic elastic modulus of the air-dry samples were slightly higher than the natural ones, and the specimens with the natural moisture content were higher than the saturated ones. This describes the inverse relationship between the dynamic elastic modulus of sandstone and the moisture content.

THE MECHANISM OF THE LOADING STRESS AMPLITUDE AND THE MOISTURE CONTENT STATE AFFECT THE SANDSTONE'S DYNAMIC PROPERTIES.

Rock sample component analysis

In this experimental study, the sandstone sample was brought from the Three gorges reservoir area (Shaxi town, Zigui county), which is vulnerable to landslide. The sample has no visible joints, and it has good quality. According to the results of the analysis, the sample is sericite medium grained quartz sandstone, and it has cemented calcareous pore type. Rocks are composed of quartz, feldspar, debris, mica, and etc. Lint constituents are lithic clastic, with 0.3 mm diameter, accounts for 10%; quartz debris, uniform, particle size ranges from 0.3 ~ 0.5mm, accounts for 80%; and matrix component is sericite, accounts for 10%. A typical rock microstructure is shown in Figure 10.

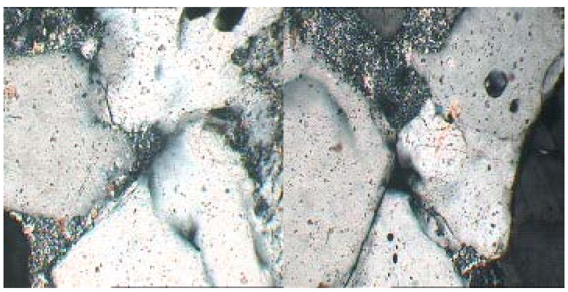


Figure 10: typical micro-structure of the sandstone slice

Analysis of the stress amplitude

Rocks are heterogeneous materials, within which there are different kinds of dispersed cracks, pores, holes and other microscopic defects. The cementation interface between the mineral particles is a relatively weak surface. Rock strength under cyclic loading is often lower than its static strength. For liner elastic rocks, the loading and unloading paths are completely overlapped. For successive loading and unloading, the stress and strain paths are always the same, and they trace the same line back and forth. Considering inelastic rocks, such as elastoplastic rocks, when the unloading point exceeds the yield point, the unloading curve do not coincide with the loading curve and the plastic hysteresis loop will be formed. During successive loading and unloading, the maximum applied load will be the same as the initial applied load, and it will establish a hysteresis loop. As shown in Figure 11, the hysteresis loop was more likely slender and the deformation was closely elastic deformation.

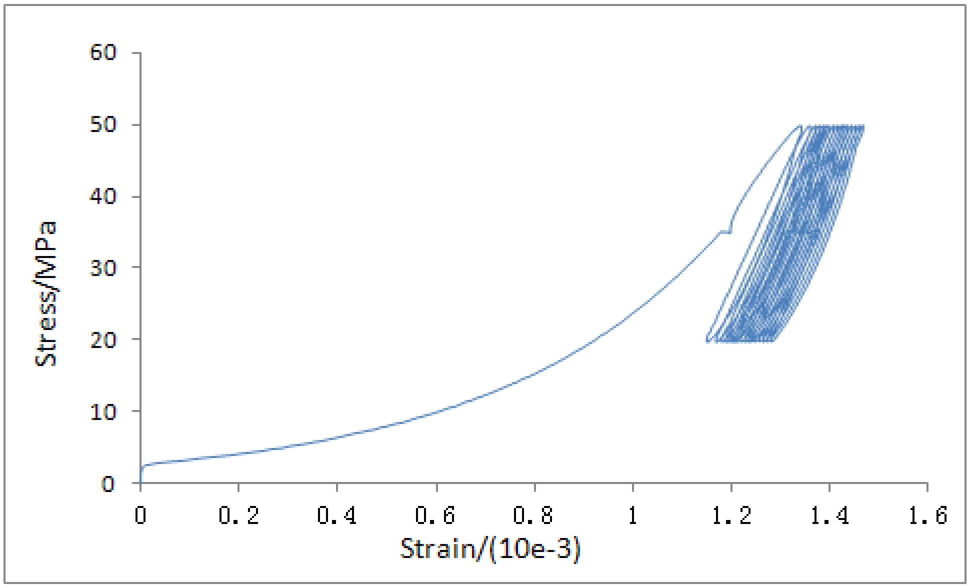


Figure 11: typical stress-stain curve of stable stress amplitude

While the loading and the unloading were done repeatedly, the maximum applied load was higher than the previous one. This loading method was used in this experimental study as shown in Figure 3. The hysteresis loop area was enlarging while the number of cycles increased. It is evident that, the hysteresis loop areas were linearly increasing while the stress amplitude increased (Figure 5 and Figure 6). Besides, the shapes of the hysteresis loops were gradually enlarged at higher stress amplitude, and the trend became significantly considerable.

As it can be seen from Figure 7 and Figure 8, the increase in the stress amplitude yielded a reduction in the damping coefficient and damping ratio, and the trend exhibited power function. The dynamic elastic modulus of the rock increased linearly (Figure 9).During loading and unloading, the cracks, pores, voids and other microscopic defects repeatedly closed, opened and enlarged. , The accumulation of the microscopic damage resulted plastic deformation.

Analysis of the effect of moisture content

Inside the rocks there are often large numbers of dispersed microscopic defects, such as micro-cracks, propagation of fissures., Especially plastic zones of cracks and crack tips are active zones of the water-rock physics, chemistry and penetration. ,. On the one hand, the water molecules penetrate the rock together with the micro-cracks and the contact surface between the micro-crack and the other structural particles. The lubrication and softening effect reduced the coefficient of internal angle of friction and cohesion of the rock. On the other hand, the gradual built up of the water-rock physics and chemical reactions or ion exchange will develop new secondary minerals, and change the internal structure of the rock. Under the action of the water pressure, the concentrated stress at the crack endpoint would likely cause crack propagation, expansion, and develop pipes that facilitate the flow of water through the rock specimen., This resulted fast rate of alteration, and a rapid change in microstructures. Combining these results, one can see that, cyclic loading and unloading stresses mainly affected the elastoplastic properties of rocks, the accumulation of plastic deformations, and the development of elasticity. The damping characteristics of the rock was weakened due to the infiltration, lubrication and softening effect of the water and the change in the water pressure inside the rock. Therefore, as the cyclic loading stress amplitude increased, the dynamic elastic modulus of the rock gradually increased, and the damping parameters decreased. The dynamic elastic modulus, damping, and damping ratios of the rock were gradually reducing while the moisture content of the rock increased.

CONCLUSION AND RECOMMENDATION

Under cyclic loading and unloading, the shape of the stress-strain hysteresis loop was not only dependent on the rock properties, but also closely dependent on the moisture content and the stress amplitude. The less the moisture content and the higher the stress amplitudes are, the slender the hysteresis loops. The smaller the moisture content of the rock samples are, the larger the hysteresis loops area., The strain fatigue has been increasing while the dissipation of energy increased.

As the moisture content of the rock samples increased, the sandstone damping coefficient, the damping ratio, and the dynamic elastic modulus decreased. The air dry samples exhibited higher dynamic parameters than the rock specimens with the natural moisture content. Similarly, the rock specimens with the natural moisture content had higher values of dynamic parameters than the saturated ones.

With the increase of the cyclic loading stress amplitude: the sandstone damping ratio and the damping coefficient decreased and showed a power function $\lambda = a f^b$ (*a*, *b* are fitting parameters, $a > 0$, $b<0$).The damping ratio and the damping coefficient were reduced by 188% and 49% respectively. The dynamic elastic modulus increased linearly. In contrast, the stress amplitude had a significant impact on the damping ratio and the dynamic elastic modulus.

According to the experimental study of this paper, the influence of the degree of moisture content and stress amplitudes on the dynamic properties of the sandstone's was clearly noticeable., Therefore, one should consider the influence of moisture content and stress amplitude during computation and selection of structural dynamic parameters. Selection of the appropriate dynamic parameters conforms to the real engineering problem.

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