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# Experimental Study on the Deformation Characteristics of Rockfill Materials under Cyclic Loading of Spherical Stress

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## Abstract

Periodic fluctuation of reservoir water level will cause periodic loading-unloading of pore water pressure and effective stress of rockfill materials for dam construction, resulting in change of stress state and internal force equilibrium of rockfill materials; the stress state of rockfill body shows that deviatoric stress basically keep constant meanwhile spherical stress is cyclic change with the rise and fall of water level. In order to investigate the deformation characteristics of rockfill materials under cyclic loading of spherical stress, the rockfill materials are used as the study object to implement a series of stress path controlled triaxial tests under the low-speed cycling state of spherical stress; in the test, the periodic change of pore water pressure of the anisotropic consolidation specimen is controlled, the stress state of rockfill materials for dam under the rise and fall of water level is simulated, and the periodic deformation characteristics of rockfill materials are measured in real-time. The test results show that: the shear strain of specimen basically exhibits the trend of step rise and elastic-plastic change law in the process of basically constant deviatoric stress and cycling of spherical stress, and the volumetric strain basically shows the variation trend of approximate elasticity; the initial stress ratio has obvious effect on the volumetric strain, the cycle number has no significant effect on the cumulative of volumetric deformation, and the cyclic amplitude of the spherical stress has little influence on the volumetric strain; the initial stress ratio has little influence on the shear strain, the cyclic amplitude of the spherical stress has significant influence on the shear strain, and there is the largest increase amplitude of the stain in the first cycle which decrease gradually along the cycles; there are an interval value of stress ratio independent of the test stress condition for the same material, and the shear strain will increase significantly when greater than the value.

## Key words

Rockfill material, Cycle loading of spherical stress, Triaxial test, Deformation characteristics.

## 1. Introduction

For the earth-rockfill dam and slope of reservoir, the fluctuation of water level often cause large deformation of dam body and slop instability. In 1963, there is large scale landslide of dam due to the continuous rainfall and the water level rise and drop during short interval by controlled of the Vajoint reservoir in Italy [1]. In June 2003, landslide instability occurred in Qianjiangping when the impounding water elevation of the Three Gorges Reservoir reached 139 m [2, 3]. When the water elevation of the Three Gorges Reservoir periodic fluctuates in the range of 145-175m during the operation period, the Baijiabao landslide in the reservoir area occurred different degrees of stair-step deformation with the fluctuation of reservoir water level [4]. The monitoring data of the Gepatsch Dam, Infiernillo Dam, etc. also reflected that the upstream of rockfill dam occurred significant collapse settlement affected by flooding and the initial impounding [5, 6]. The drying-wetting cycle resulting from the fluctuation of water level or rainfall and evaporation frequently causes the unrecoverable deformation of dam and slope. The main reasons are analyzed as follows [7]: periodic fluctuation of water level due to the power generation and flood control, the infiltration or seepage of water results in the change of groundwater seepage field in dam body, leading to the periodic loading-unloading of pore water pressure and effective stress of the dam body, and then the stress state and internal force equilibrium of the dam body accordingly the deformation characteristics of the dam body will changed under the cyclic loading effect.

For the rockfill dam, the stress state basically shows that the deviatoric stress is constant and the spherical stress is reciprocating cyclic during the rise and fall of water level and the deformation of rockfill materials will be continuous development when the stress state constant cycling. Up to now, many scholars have carried out relevant research on similar stress path conditions. Kuwano et al [8] conducted a triaxial drainage test ($q_c/p_c$ = 0.7) for Ham River sand (HRS) (Dr = 25-30%) under the condition of equal stress ratio consolidation. The results show that, Under the condition of deviatoric stress, the volumetric strain significantly increases with the increasing of the spherical stress, when the spherical stress decreases, the shear strain decreases slightly. The volumetric strain decreases significantly with the decrease of the spherical stress, while the shear strain changes very slightly in the initial stage, followed by a quick increase with its curve exhibiting a significant turning point. Lourenco et al [9] conducted the triaxial test by the stress path of constant shear strain and decreased effective spherical stress through increasing the pore water pressure for the Silica sand. The research result shows that: The volumetric strain of specimen shows dilation under the condition of different initial relative densities and stress ratios, while the axial strain shows the change from initial slow increase to sharp increase. Anderson and Sitar [10] applied the test for the undisturbed colluvial soil adopted the stress path of decreased effective spherical stress and constant deviatoric stress by increasing the pore water pressure. The volumetric strain of specimen shows dilation, while the axial stress is increased; The strain occurs transition when the stress path passes through the failure line, and the soil cannot meet the condition of constant deviatoric stress; At same time, both the deviatoric stress and the spherical stress are decreased, the volume occurs dilation and the axial strain is sharply increased, showing an obvious transition. Jung and Finno [11] compared the deformation characteristics of the remolded clay and the Chicago glacial clay, for the stress path with constant deviatoric stress and monotonic loading or unloading of spherical stress, the volumetric strain increases or decreases with the increase or decrease of the spherical stress. There is obvious shear strain for these two types of clay: the shear strain is decreased with the loading of the spherical stress, and increased with the unloading of the spherical stress. Yasufuku et al. [12] studied the deformation characteristics of Aio sand under cyclic spherical stress along with constant deviator stress, when the constant stress ratio consolidation is completed (qc/pc = 0.8). The results show that although the number of cycles is small (only for two cycle periods), the volumetric strain and shear strain both accumulated significantly. Chen used remodeling silty clay to carry out cyclic triaxial tests under constant deviator stress. The change of effective spherical stress was achieved by adjusting the backpressure ($q_c/p_c^{'}$=0.5～0.6), in this test, the volumetric strain was basically changing in elastic cycles, and there is no obvious accumulation, while shear strain is significantly accumulated, and the increasing amplitude in the first cycle is the largest, while it gradually decreases afterwards.

The above-mentioned studies show that the relevant research object focus on the sands and clays mostly, while there is few research on the rockfill materials, it is difficult to understand the deformation characteristics of rockfill materials under the stress path. In view of this, this research focus on rockfill materials using triaxial test system under the anisotropic condition, and simulated the rise and fall of water level by controlling the cyclic change of pore water pressure, the shear strain and volumetric strain of specimen are be measured during this stress path condition. The deformation law of the rockfill materials will be further studied under the cycling of spherical stress.

## 2. Test Material

The rockfill materials used in the test are taken from the fields of a certain hydropower station, and the parent rock is sandstone and slate. The maximum diameter of the original rockfill materials is 600mm, and the testing grading is obtained from the original grading adopted the mixed scaled method. The maximum diameter of the test rockfill materials is 40mm. And grain-size distribution curve of the original material and test material are shown in the Fig. 1. The specimen used for this research has a diameter of 200mm and height of 400mm, and the dry density of samples is 2.18g/cm$^3$ (Dr=0.90).

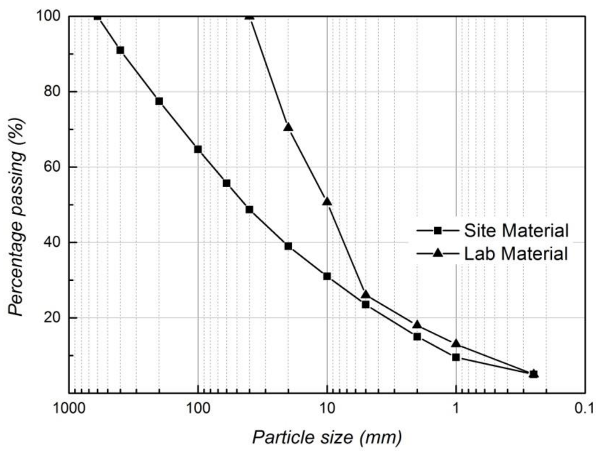


Fig.1. Grain-size distribution curve of the test material

## 3. Test Equipment

The GCTS stress path triaxial instrument is used for this research, and the confining pressure, pore water pressure and axial pressure are provided through the servo pressure controller, with the pressure control accuracy of 0.5kPa. The change of water volume in the cell and specimen can be measured by using the pressure/volume controller for the confining pressure and pore water pressure, with the volume measurement accuracy of 0.01ml.

## 4. Test Procedure

Before the test, the corresponding confining pressure and axial pressure are be calculated according to the designed deviatoric stress and spherical stress. Firstly, the confining pressure and axial pressure shall be imposed on the specimen in order. Secondly, the specimen shall be saturated using the degassed water with the water head of 60cm after the axial strain of the first step becomes basically stable ($\varepsilon_1 \leq 0.0006\%/\text{min}$). Thirdly, the cycle test can be started when there is continuous outflow water without bubbles from the drainage pipe on the top of specimen meanwhile the axial strain becomes basically stable ($\varepsilon_1 \leq 0.0006\%/\text{min}$). The reason of adopted the axial strain value is to maximally eliminate the impaction of creep deformation of the materials. During the test, the confining pressure and deviatoric stress shall be kept constant, and the stress path of decreased effective spherical stress and constant deviatoric stress shall be realized by increasing the pore water pressure in the specimen. Meanwhile, the cycle frequency of the pore pressure is set at 0.001HZ in order to guarantee no excess pore water pressure during the test, and test process can be regarded as a quasi-static process due to the low cycle frequency. The loading waveform of the pore water pressure is triangle wave, and the typical loading path is shown in Fig. 2.

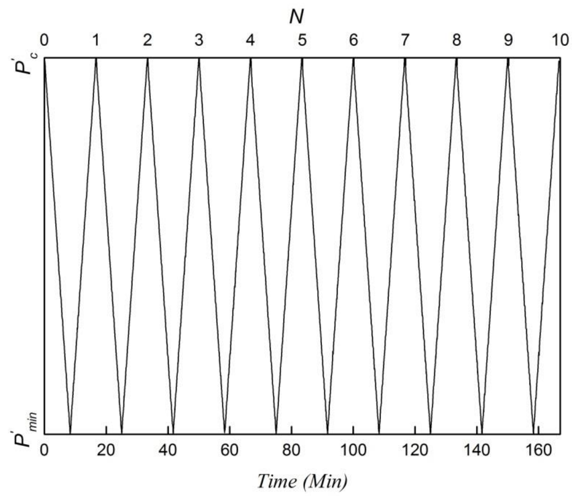


Fig. 2. Revolution of spherical stress with time/cyclic number

The effective spherical stress cycle in each cycle is divided into two stages. The first stage: as the pore water pressure increases, the effective spherical stress starts to decrease from the initial effective spherical stress $p'_c$ and continues to decrease until the minimum value $p'_{min}$, the change range is from $p'_c$ to $p'_{min}$; The second stage: as the pore water pressure decreases, the effective spherical stress increases from the minimum value $p'_{min}$ until the initial effective spherical stress $p'_c$, the change range is from $p'_{min}$ to $p'_c$.

This research uses two stress paths: the first stress path has the same initial effective spherical stress $p_c'$, different initial effective deviatoric stress $q'_c$ and the same cyclic amplitude $\triangle p'$ of spherical stress; while the second stress path has the same initial effective stress $p_c'$ and initial effective deviatoric stress $q'_c$, and different cyclic amplitude $\triangle p'$ of spherical stress.

The stress and strain used in this paper are expressed by using the following formula: effective spherical stress $p'=(\sigma'_1+2\sigma'_3)/3$, effective deviatoric stress $q'=\sigma'_1-\sigma'_3$, and stress ratio $\eta=q'/p'$, where $\sigma'_1$ and $\sigma'_3$ respectively indicates the effective axial stress and effective ambient stress, $p_c'$ is the effective initial spherical stress, $q_c'$ indicates the initial effective deviatoric stress and $\eta_c$ indicates the initial stress ratio. The volumetric strain of specimen $\varepsilon_v=v_{internal}/v_0$, where: $v_{internal}$ indicates the water volume change in specimen resulting from the pore pressure cycling and $v_0$ indicates the volume of specimen before the cyclic loading. In the result analysis, the volume dilation indicates negative and volume compression indicates positive; shear strain $\varepsilon_s=\varepsilon_1-1/3\varepsilon_v$, where $\varepsilon_1$ indicates the axial strain.

## 5. Development Law of Volumetric Strain

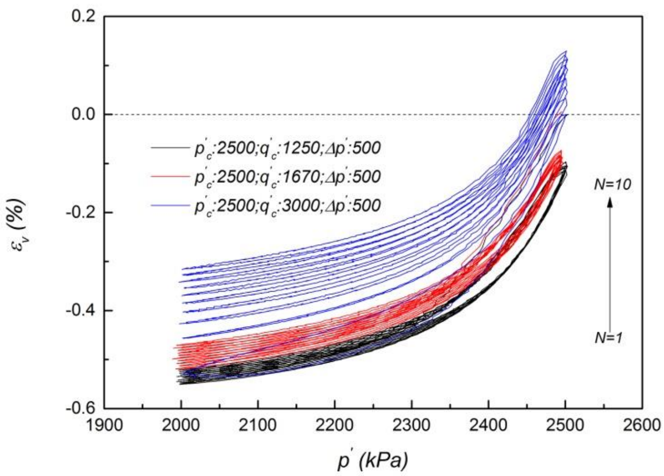


Fig.3. $p'$-$\varepsilon_v$ curve (the value of $q'_c$ is different)

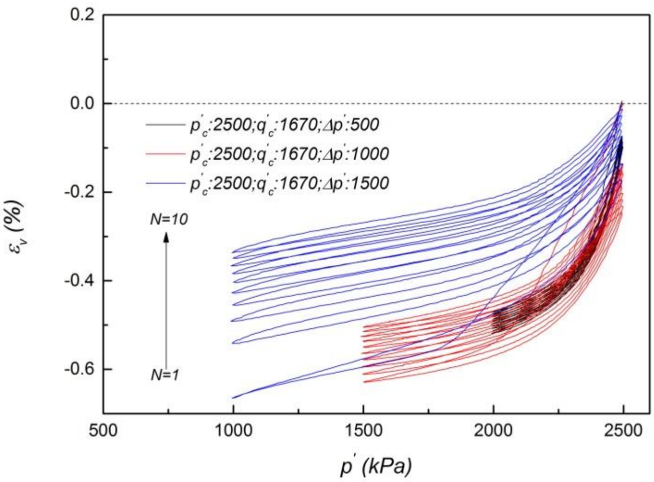


Fig.4. p'-$\varepsilon_v$ curve (the value of$\Delta p'$ is different)

The development law of $\varepsilon_v$ of specimen under the two stress paths is as shown in the Fig. 3 and Fig. 4. It shows that: under the two different stress path conditions, $p_c$' of specimen is smaller than the initial value during the whole process of test with the development of $\Delta p'$, and the volume deformation of specimen basically shows shear dilatation. The volumetric strain shows the law of approximate elastic change as a whole with the change of $\Delta p'$, and its change trend is on the contrary with the increase and decrease path of the pore water pressure. Where:

Under the first stress path condition, $\varepsilon_v$ develops to shear contraction when $q'_c$ is 3000, and $\varepsilon_s$ is 0.1% (shear contraction) after 10 cycles; $\varepsilon_v$ is shear dilatation when $q'_c$ is 1250 and 1670, and $\varepsilon_s$ is -0.1% (shear dilation) after 10 cycles; this reflects that, under the condition of the same $p_c$', $\varepsilon_v$ shows a trend of development from shear dilatation to shear contraction with the increase of $q'_c$.

Under the second stress path condition, it has the same $p_c$' and $q'_c$. Under the three kind of the $\Delta p'$, $\varepsilon_v$ shows shear dilation and the final cumulative deformation difference is small. Thus, it can be believed that the cycle stress amplitude has a minor impact on the volumetric strain of specimen.

The main reasons are analyzed as follows: the increase of pore water pressure results in the decrease of the effective spherical stress and the dilation of the volume; on the contrary, the effective spherical stress p' is restored to its initial value when the pore water pressure is reduced from the maximum value to the initial value 0. Under these conditions, the volume deformation of specimen shows different degrees of shear dilation or shear contraction under different stress conditions, but it is less significant.

## 6. Development Law of Shear Strain

The development law of shear strain $\varepsilon_s$ under the two stress path conditions is shown in the Fig. 5 and Fig. 6. In accordance with the Figures, the change of $\varepsilon_s$ with $\triangle p^{'}$ basically shows the law of elastic-plastic change under the two different stress path conditions, and its change trend is the same with the increase and decrease path of the pore water pressure. The $\varepsilon_s$ shows a trend of stair-step development and overall rise as a whole, and the strain amplification reaches the largest value in the first cycle and then becomes smaller gradually. The constant increase of shear strain is mainly caused by the accumulation of plastic shear strain which cannot be recovered.

Under the first stress path condition, $\varepsilon_s$ has a minor difference when $q^{'}_c$ are 1250 and 1670, and $\varepsilon_s$ is about 0.25% after N=10 cycles; $\varepsilon_s$ achieves 1.2% when $q^{'}_c$ is 3000. This reflects that there is a transition interval between the initial strain conditions, and there is an obvious difference in the development law of shear strain before and after this interval.

Under the second stress path condition, $\varepsilon_s$ increases with the increase of the $\triangle p^{'}$. Where: $\varepsilon_s$ has a minor difference when $\Delta p^{'}$ are 500 and 1000, and $\varepsilon_s$ is 0.25% after N=10 cycles and 0.5% respectively; $\varepsilon_s$ approaches 1.4% when $\Delta p^{'}$ is 1500. Similar to the development law of shear strain under the first stress path condition, there is also a transition interval influencing the shear strain.

The reasons are as follows: under the state of anisotropic compression stress, each loading process of pore water pressure will cause the decrease of the effective spherical stress, resulting in the sample approaching to the critical failure state of soil and damage of internal structure of the rockfill materials. The elastic part in the shear strain can be recovered when the effective spherical stress recovers to the initial value, but the plastic shear strain formed in each cycle cannot be recovered, leading to constant and cumulative increase of the whole shear strain.

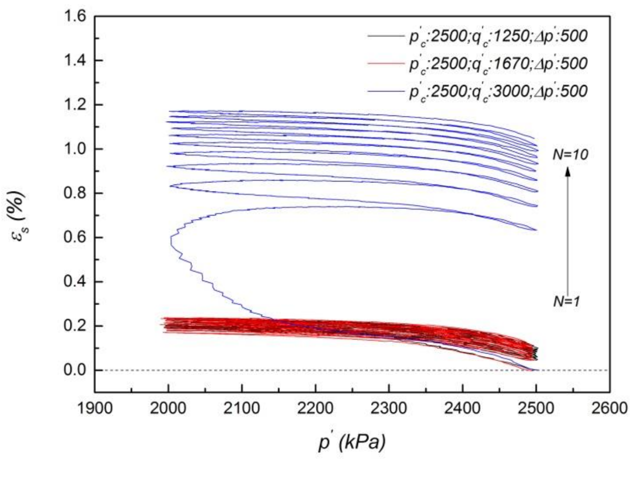


Fig. 5. p'-$\varepsilon_s$ curve (the value of $q^{'}_c$ is different)

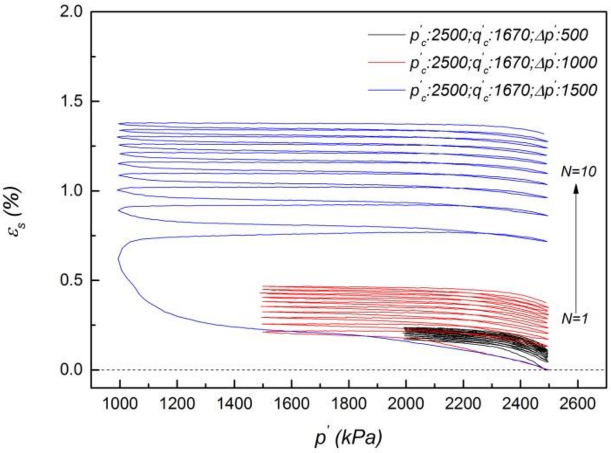


Fig. 6. p'-$\varepsilon_v$ curve (the value of$\Delta p'$ is different)

## 7. Influence of Stress Ratio on the Shear Strain

Pri ea nos In accordance with the development law of the shear strain under the two stress path conditions, there is a transition interval between the stress conditions and there is a significant difference in the development law of shear strain before and after this transition interval. Accordingly, the corresponding relationship between the dynamic development of stress ratio and shear strain during the test is analyzed. The stress ratio η in the test will occur cyclic change with the decrease or increase of the pore water pressure. Under the first stress path condition, $\eta_c$ is different, and in each cycle, η increases firstly and then decreases to the initial value; under the second stress path condition, it has the same $\eta_c$, and in each cycle, η increases firstly and then decreases to the initial value. The relationship between the η and $\varepsilon_s$ under the two stress conditions is shown in the Fig. 7 and Fig. 8.

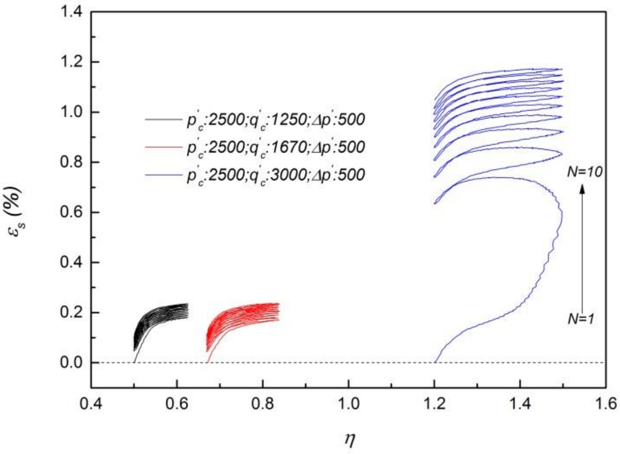


Fig.7. $\eta$-$\varepsilon_s$ curve(the value of $q'_c$ is different)

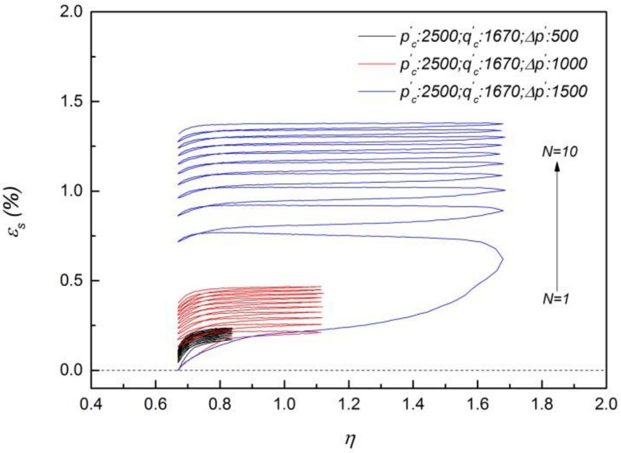


Fig.8. $\eta$-$\varepsilon_s$ curve(the value of $\Delta p'$ is different)

Under the first stress path condition, $\eta_c$ corresponding to the q value of 1250, 1670 and 3000 is respectively 0.5, 0.67 and 1.2, which cycles within 0.5 ~ 0.63, 0.67 ~ 0.84 and 1.2~ 1.5 respectively. Under the first two stress conditions, the cycle process of spherical stress has no significant shear strain; when q is 3000 and $\eta$ exceeds 1.4 approximately, the shear strain will be significantly increased.

Under the second stress path, $\eta_c$ under cycle amplitudes of three kinds is all 0.67. The maximum stress ratio in the test will be also different due to the different amplitudes, and the change range are 0.67 ~ 0.84, 0.67 ~ 1.11 and 0.67~ 1.67. In which, the maxim stress ratio is 0.84 and 1.11 respectively when $\Delta p'$ is 500 and 1000, and the shear strain at this time is not obvious; when $\Delta p'$ is up to 1500 and $\eta$ exceeds about 1.4, the shear strain is significantly increased.

From the above-mentioned test results under the two different initial stress states and cyclic stress conditions, it can be seen that there is a transitional interval value of the stress ratio for the same type of test materials with the same sample condition; when it is smaller than this interval value of the stress ratio, the shear strain mainly shows elastic cycle and the cumulative shear strain is not significant with the increase of the cycle; when it is larger than this value, the particles in the specimen move with each other and the structural damage is obvious due to the increase of the stress ratio, and the shear strain sharply increases from the elastic stage to the plastic stage, which makes the shear strain increase significantly.

## Conclusion

The cyclic change of the effective spherical stress is realized by controlling the pore water pressure. For the same testing materials, the experimental study is carried out on the deformation characteristics of rockfill materials under the low-speed cycle effect of spherical stress, and the development law of strain under different stress conditions is compared to draw the following conclusions.

(1) The decrease of the effective spherical stress will significantly result in the dilation of the specimen; the volumetric strain exhibits the trend of approximately elastic change; The initial stress ratio has a relatively obvious influence on the volumetric strain, and the higher initial stress ratio will cause the specimen to occur shear contraction; the cycle number has no significant impact on the cumulative effect of deformation; the cyclic stress amplitude has less influence on the volumetric strain.

(2) The shear strain basically shows a trend of elastic plastic change. The initial stress ratio has little influence on the shear strain, and the cyclic stress amplitude has a more pronounced influence on the shear strain. The initial cycle has the largest strain amplitude and then decreases gradually with the increase of the cycle.

(3) There is a transitional stress ratio interval value in the development of the shear strain of the same material, and this value is independent of the test stress condition. When the stress ratio exceeds this interval value, the shear strain will be significantly increased. For the materials used in this research, the transitional stress ratio is about 1.4.

According to the laws revealed in this paper, the deformation law of rockfill materials under cyclic path can be studied. In this paper, only one type of rockfill material with the same sample preparation density is selected, so the conclusion has some limitations and the applicability of the research results needs to be further studied.

## Acknowledgements

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