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Research on Rheological Properties of Rockfill Material under Stress Unloading

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Research on Rheological Properties of Rockfill Material under Stress Unloading

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Abstract. A number of super high earth-rock dams will be built in China in the near future. Deformation control is the key issue in the safety construction and operation of these major water conservancy projects.In this paper, the effect of stress loading process on the subsequent rheological development is studied, and a new accumulation rule of rockfill rheology is proposed, that is, the current rheological variable of rockfill unit at a certain time is equal to the hardening rheological variable that can cause additional hardening of rockfill at that time.Then, the influence of stress unloading process on the subsequent rheological development law is further studied. It is found that after stress unloading, there are positive rheological zone, no rheological zone and reverse rheological zone in the rheological behavior of rockfill material. The rheological accumulation rule proposed in this paper is also applicable to the case of stress unloading.

1. Introduction
Deformation control is the key issue in the safety construction and operation of these major water conservancy projects. Among them, the control of dam deformation in the later stage is particularly critical. At present, Shenzhujiang rheological calculation model widely used in earth-rock dam engineering is mainly based on constant load rheological test. Whether it is suitable for complex loading is a subject worthy of further study. In this paper, the influence of stress loading process on subsequent rheological development law is studied, a new accumulation rule of rockfill rheology is proposed, and the influence of stress unloading process on subsequent rheological development law is further studied.

2. Rules of Rheological Accumulation of Rockfill Materials

2.1. Rockfill rheology accumulation rules overview
In China, Academician Shen Zhujiang first carried out systematic research on the rheology of rockfill materials, and the rheological calculation method of earth-rock dam is still the most commonly used method. The empirical function rheological model based on stress-strain rate is usually used in the rheological calculation model of rockfill material established by academician Shen Zhujiang. In order to obtain the rheological deformation rate of rockfill unit at a certain time, only the current cumulative rheological deformation at that time (referred to as current rheological deformation) can be determined. The rule of determining the current rheological deformation at any time of rockfill unit is the cumulative
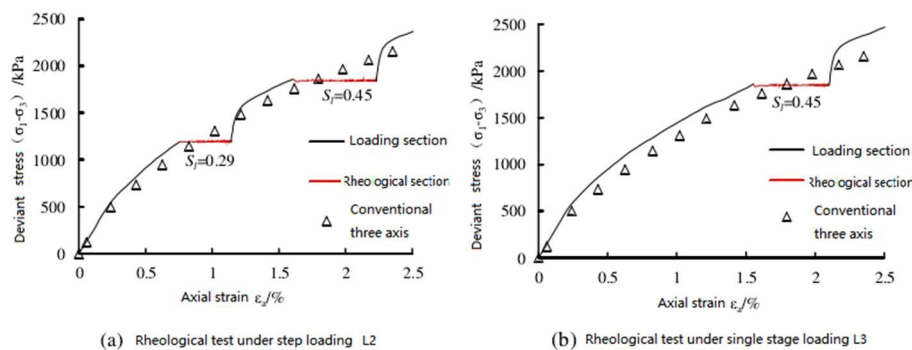
rule of rheological deformation. At present, the two main cumulative rules are the original Shenzhujiang rheological model and Qian Xiaoxiang's model.

2.2. Cumulative Rules of Rheology under Stress Incremental Loading
This paper only considers the case of stress incremental loading. Large stress incremental loading rheological test refers to the test in which the stress increment increases greatly after the rheological loading of rockfill specimens, and the stress point after loading has reached or exceeded the yield surface after the previous rheological expansion. Fig. 1   presents the experimental results of stress-strain relationship curves of step-loading rheological test L2 and single-stage loading rheological test L3 under confining pressure σ_3==800kPa, respectively. Among them, the second stage rheological test of stage loading rheological test L2 is in the same stress state as that of single stage loading rheological test L3 (S_l=0.45).

In the stage loading rheological test L2, after the completion of the first stage rheological test ($Sl =$ 0.29), the plastic deformation under instantaneous loading is very obvious. Therefore, the second stage rheological test of stage loading rheological test L2 belongs to the case of large stress incremental loading rheological test after rheological test.
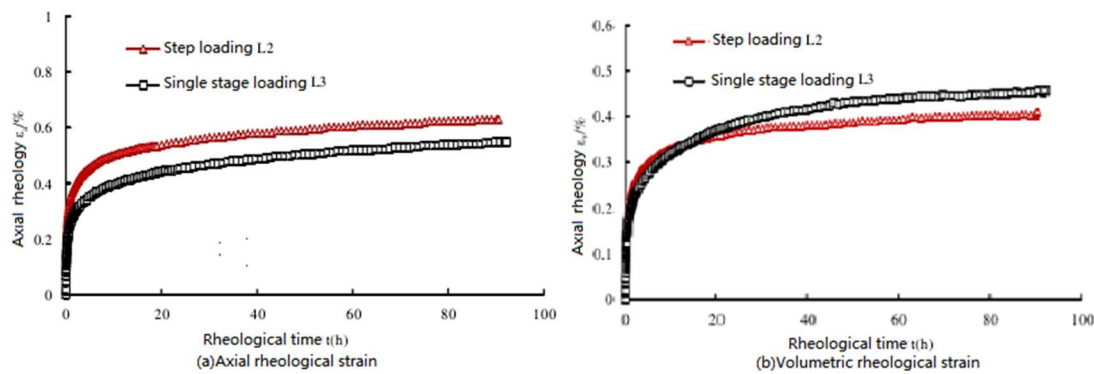

(a) Rheological test under step loading L2   (b) Rheological test under single stage loading L3

Fig. 1 Comparison of Stress-Strain Relation Curves for Graded and Single-stage Loading Rheological Tests(σ 3=800kPa)

Table 1 gives a summary of the final rheological parameters of step-loading triaxial rheological test L2 and single-stage loading rheological test L3. As can be seen from the data in the table, The final axial flow of the second stage rheology (S_l = 0.45) obtained in the step loading rheological test L2 is $\varepsilon_{af}^c = 0.63\%$, the final volume rheology is $\varepsilon_{af}^c = 0.41\%$, Its magnitude is close to the final rheological quantity $\varepsilon_{af}^c = 0.55\%$ and $\varepsilon_{af}^c = 0.46\%$ obtained from single stage loading rheological test L3 with the same stress level. The numerical difference between the two can be attributed to the experimental error. According to the Shenzhujiang rheological accumulation rule, the final rheological parameters of the second stage of the step loading rheological test should be the sum of all the rheological strains that occurred before the specimen. According to this rule, the ultimate axial rheological strain of the stage is $\sum \varepsilon_{af}^c = 1.01\%$, the final volume rheological strain is $\sum \varepsilon_{af}^c = 0.80\%$ .These two values are far greater than the corresponding values of single stage loading rheological test L3. This shows that the original Shenzhujiang rheological accumulation rule is not suitable for the cumulative calculation of rheological strain of rockfill materials under the condition of stress variation.
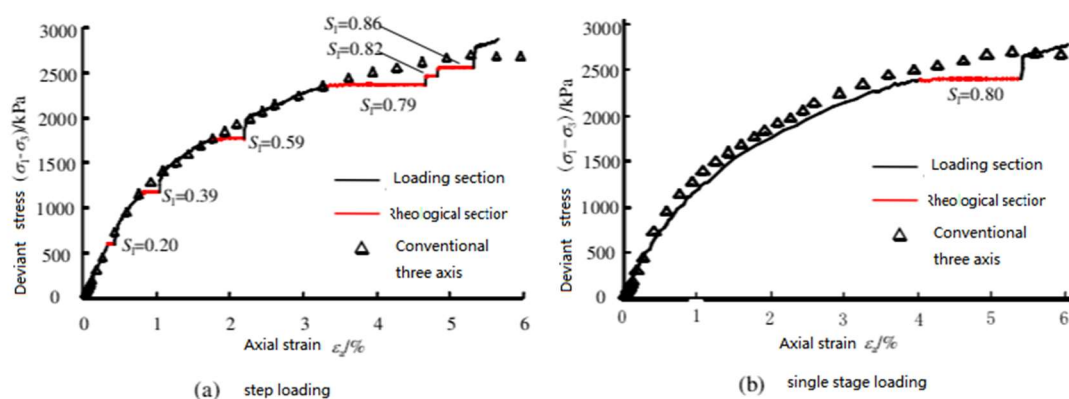
Table 1. Summary Table of Final Rheological Fluxes for Graded Rheological and Single-stage Rheological Tests(σ 3=800kPa)

test	Stress level	Axial rheology(%)	Volume rheology(%)
Graded rheologyL2	0.29	0.38	0.39
	0.45	0.63	0.41
Single stage rheology L3	0.45	0.55	0.46

Figure 2 shows a comparison of the rheological time curves of step loading and single stage loading rheological tests at the stress level $S_l = 0.45$. It can be seen from the graph that within the allowable range of test errors, the time evolution process of the two methods is basically the same. It can be concluded that for the rheological test under large stress incremental loading after rheological treatment, the rheological behavior before the stress level (S_l=0.29) has little effect on the subsequent rheological process.

Fig.2 Contrast Diagram of Rheological Process of Graded and Single-stage Loading Tests (σ 3=800kPa, S_l =0.45)

Karimpour also carried out the rheological test of Nuozhadu rockfill under 600 kPa confining pressure. The rheological test results were compared with those under single-stage loading. Figure 3 shows that the corresponding summary table of the final rheological parameters is shown in Table 3.2. The final rheological deformation values of the step-loading rheological test and the single-stage loading rheological test at stress level lS=0.80 are basically the same as those obtained in this paper. The conclusions reached are consistent.

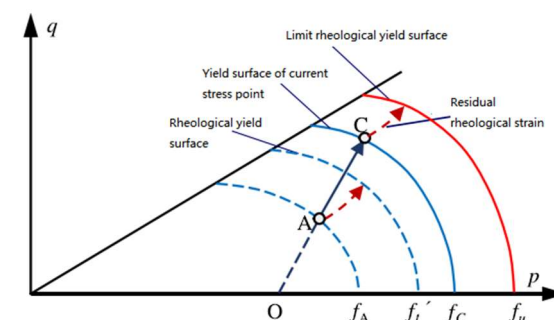**Fig. 3** Comparison of stress-strain curves of graded and single-stage loading rheological tests(σ 3=600kPa)

Table 2 Summary Table of Final Rheological Variables for Graded Rheological and Single-stage Rheological Tests(σ 3=600kPa)

Test	Stress level	Axial rheology(%)	Volume rheology(%)
Graded rheologyL2	0.20	0.09	0.23
	0.39	0.24	0.17
	0.59	0.45	0.21
	0.79	1.37	0.23
Single stage rheology L3	0.80	1.38	0.22

From the above analysis, we can draw the following conclusion: after large stress incremental loading, all the rheology before the rockfill unit will not affect the rheological process after the unit. That is to say, when the rock-fill element undergoes plastic deformation under stress loading and the new stress state is above the yield surface, the current rheological variables of the rock-fill element will be cleared, and all the rheological variables need to be recalculated. After large incremental stress loading, the current rheological yield surface of the specimen coincides with the yield surface of the current stress point due to the instantaneous loading plastic deformation, which indicates that the hardening rheological and equivalent load increment are zero at this time. Therefore, for the case of large stress incremental loading, the current rheological flux of rockfill is equal to hardening rheological flux, and both of them are equal to zero.

2.3. Summary of Rheological Rules under Large Stress Incremental Loading
Fig. 4 shows the rheological process diagram under the condition of large stress increment loading. After loading to point A, the specimen undergoes rheological behavior under constant stress. The occurrence of rheological strain causes the yield surface to expand to the rheological yield surface ft'. Then, a large stress increment is applied to point C, which lies outside the rheological yield surface f 4'. Therefore, the current rheological or hardening rheological strain of the specimen at point C is zero. When the loading is continued from point C, the rheology in the early stage of the specimen will not affect the loading characteristics in the later stage.
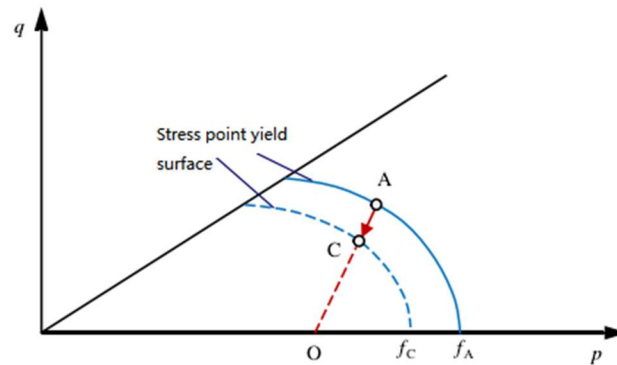

Fig. 4 Rheological process under large stress incremental loading

Current rheology leads to hardening; conversely, the rheology leading to hardening is the current rheology. The influence between stress loading and rheological process is unified, and is harmonious and symmetrical at the level of physical action.
3 Study on rheological characteristics of stress unloading
The typical stress path of rheological test after stress unloading is shown in Fig. 5. The specimens were first monotonically loaded to the stress point A under the conventional triaxial loading condition, and then the stress point A was located on the yield surface f_A. Then, unload to stress point C. To carry
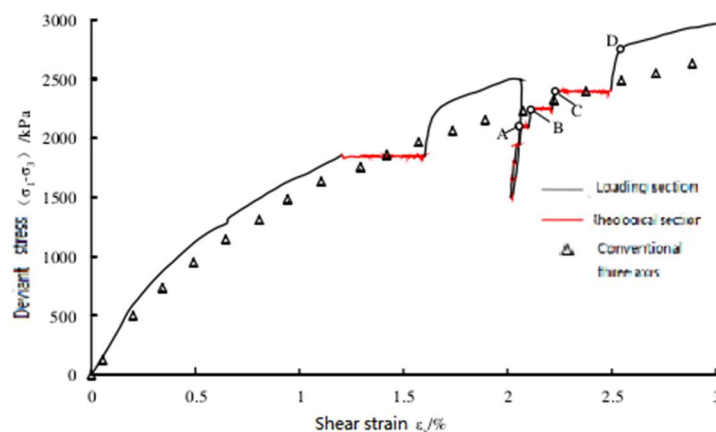
out rheological test at C point while keeping stress state unchanged is to carry out rheological test after stress unloading.

Fig. 5 Rerheological test after unloading

Fig. 6 shows the results of the graded rheological test UL3 under stress unloading. Before the stress unloading, the rheology of the test under the first-order large stress incremental loading was carried out. According to the previous research results in this paper, after large stress incremental loading, the previous rheology has no effect on the subsequent rheological process. Therefore, this section focuses on the results of rheological tests after stress unloading.
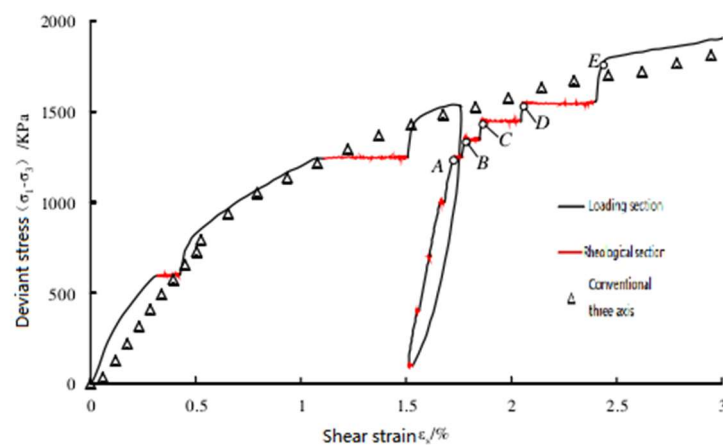
It can be seen from Fig. 6 that after consolidation of rockfill specimens under confining pressure of σ_3=800 kPa, the deviation stress is $(\sigma_1-\sigma_3) = 2500$ kPa, and then the axial force is unloaded to $(\sigma_1-\sigma_3) = 1500$ kPa. Then switch to stress control and proceed with rheological process. After the rheological stability, the constant load rheology is carried out step by step under different stress levels. It can be seen from the figure that the rheological strain is almost zero after unloading directly to $(\sigma_1-\sigma_3) = 1500$ kPa. According to the Shenzhujiang rheological calculation model, the rheological strain should be determined by the stress state after unloading. So we have $\varepsilon_{sf}^{c} = 0.34\%$,and $\varepsilon_{vf}^{c} = 0.37\%$,It is inconsistent with the test results. This shows that the stress unloading process and the subsequent rheological process are not independent of each other. The stress unloading process changes the current rheological cumulant, which has an important impact on the subsequent rheological process.

Fig. 6 Stress-strain curve of UL3 rheological test after stress unloading(σ 3=800kPa)

After that, the deviation stress value is gradually increased, and almost no rheological strain occurs at (σ1 -σ3) = 1650 kPa, 1800 kPa and 1950 kPa, until the deviation stress increases to (σ1 -σ3) = 2100 kPa, i.e. point A shown in figure 6. After that, two small increments of stress were loaded to point B (σ1 -σ3) = 2250 kPa and point C (σ1 -σ3) = 2400 kPa respectively, which resulted in considerable rheological strain.
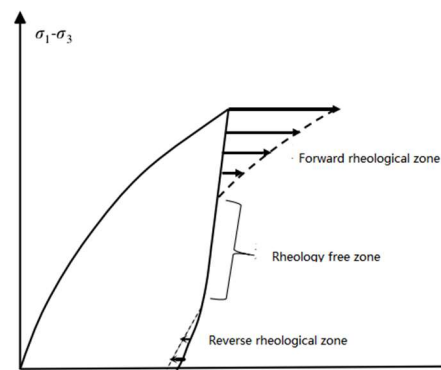
Figure 7 shows the results of UL2 test after stress unloading. Similarly, without considering the rheological process under the first two stages of large stress incremental loading, the results of rheological tests after stress unloading are mainly introduced. From Fig. 7, it can be seen that after consolidation of rockfill specimens under confining pressure of σ3=400 kPa, the deviation stress (σ1 -σ3) = 1550 kPa is loaded. Then, the deviation stress (σ1 -σ3) = 100kPa is unloaded directly, and the rheological process is carried out with the stress state unchanged. It can be seen from the figure that in the case of large stress unloading at this stage, the rockfill sample even undergoes reverse flow,which ε_{af}^{c} = -0.01%, ε_{vf}^{c} = 0.02% ,But the value is relatively small. After that, the deviation stress value is gradually increased, and the rheological process is carried out at (σ1 -σ3) = 400 kPa, 700 kPa and 1000 kPa, respectively. Similarly, almost no rheological strain occurs. It is not until the deviation stress increases to(σ1 -σ3) = 1250 kPa, i.e. to point A shown in Figure 7, that a small rheological strain begins to occur. After two stages of small stress incremental loading, the specimens were loaded to point B (σ1 -σ3) = 1350 kPa and point C (σ1 -σ3) = 1450 kPa respectively, resulting in considerable rheological strain.

Fig. 7 Stress-strain relationship curve of UL2 rheological test after stress unloading(σ 3=400kPa)

In conclusion, the rheological behavior after stress unloading can be described by the diagram shown in Figure 8. When rockfill specimens are loaded with large incremental stress (where the stress point is above the yield surface), the stress unloading occurs. With the different magnitude of stress unloading, the corresponding rheological behavior shows completely different characteristics. According to the magnitude of stress unloading, it can be divided into positive rheological zone, non-rheological zone and reverse rheological zone. In the forward rheological zone, with the increase of stress unloading, the rheological strain from constant stress state decreases gradually until it tends to zero; if the stress unloading continues to increase, the rockfill unit will enter the non-rheological zone, and there will be no rheological strain in a considerable range of rheological tests; when the stress unloading is very large, the rockfill sample will even be able to produce rheological strain. Reverse flow occurs, that is, there is a certain range of reverse flow zone. The phenomenon of reverse rheology may be related to the so-called unloading yielding phenomenon. The numerical value of reverse rheology is generally small and has no engineering significance, which is not the focus of this paper. Lade and Tatsuoka also found similar rules in unloading rheological tests of sand and clay.

Fig. 8 A sketch of rheological development under different unloading conditions

3. Conclusion

Based on the results of graded rheological tests under stress unloading, the effects of different stress unloading processes on subsequent rheological development are analyzed and summarized in this paper. The main research results are as follows: After stress unloading, the rheological law of rockfill samples can be divided into positive rheological zone, non-rheological zone and reverse rheological zone according to the magnitude of stress unloading. In the forward rheological zone, with the increase of stress unloading, the rheological strain obtained by rheological flow under constant stress decreases gradually until it tends to zero; if the stress unloading continues to increase, the rockfill unit will enter the non-rheological zone, and no rheological strain will occur during the rheological test in a considerable range; when the stress unloading is very large, the rockfill sample or even the rheological strain will occur. Reverse rheology will occur with a small amount and enter the reverse rheological zone. The rheological accumulation rule proposed in this paper can be applied to complex loading and unloading conditions, and it is a universal rheological accumulation rule.

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