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Experimental Study on Landslide Early Warning Model Based on Inverse-velocity

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Abstract: Landslide instability prediction is an important content of geological disaster prevention and control. Many domestic and foreign scholars have been much relevant research, and achieved more results, among them, the Inverse-velocity method landslide early warning model is one of the short-term prediction models, which is widely used in landslide hazard prediction. In this paper, through the rheological test, the deformation characteristics of deformation point and deformation point of deformation point are analyzed and compared by analyzing the characteristics of time-displacement curve of the actual landslide monitoring and the locking section theory of Qin Si-Qing. It is noted that the model parameter value of the abrupt change point is close to the model parameter value of the failure point by contrasting the speed reversal method. It is shown that the model parameters obtained by the displacement monitoring can be utilized in landslide instability prediction.

***Keywords:** landslides; inverse-velocity method; time deformation curve; rheological test*

1. Introduction

The occurrence of landslide disasters can often cause a lot of casualties and property losses, how to accurately predict and forecast the disaster is an important research topic of the geological catastrophe research workers. As we all know, the evolution and development of landslides are influenced by many factors such as topography, geological structure and natural environment, so the deformation of landslide presents a non-linear characteristic. This is difficult to accurately predict landslide hazards. Nonetheless, research of geological hazard forecasting and forecasting has obtained more research results. The earliest landslide prediction research began in the 1960s, the Japanese scholar Saito for the first time put forward the empirical formula for landslide prediction [1], In the later period, scholars have proposed dozens of landslide prediction and prediction theory, such as: The deterministic forecasting model is Taketo Saito, creep test forecasting model, landslide deformation analysis forecasting method, limit equilibrium method, etc.; statistical forecasting model curve regression BP neural network model, synergetic bifurcation model, catastrophe theory prediction [2], and so on. The model is built on the gray model GM (1, 1), Verhulst inverse function model and Markov chain forecast. The deterministic forecasting model is generally applicable to the temporary slip predict, while the statistical forecasting model and nonlinear forecasting model are generally used in the long-term forecast. These early warning models are derived from theoretical shear failure curves of rock and soil. In practice, the early warning model of the application, generally through the slide with the rock rheology test curve to determine the parameters of early warning model. However, due to the effect of size effect, the shear deformation characteristics of the local sliding zone soil can't fully characterize the shear deformation characteristics of the entire slide body. How to determine the model parameters accurately does not have a reasonable method.

Landslide monitoring is usually a long-term process. The displacement monitoring curves of the landslide have a tendency to show stepped deformation characteristics (Figure 1), the deformation characteristics of these steps corresponds to seasonal climate changes. In the rainy season, the deformation of the landslide accelerates and slows down or stops in the dry season. The similar rheological test curve can be observed similar to the ladder-shaped deformation characteristics, which are the rheological test load formed by the ladder-shaped deformation characteristics. Are the deformation characteristics of these deformation points consistent with the deformation characteristics at the time of failure? In this paper, the similarity between the velocity step point and the deformation characteristic of the failure point in the rheological test curve is analyzed according to the locking section theory of Qin Si-qing [3] and DR friction law [4]. The deformation characteristic of the step point in the early displacement curve is deduced The Feasibility of Early Warning Model Parameters in Instability Failure. Which can remove the size effect of early warning model parameters, and the model parameters are more in line with engineering practice and more accurate.

2. Time - displacement curve of landslide

Displacement monitoring of landslide is one of the important methods to prevent and control geological disasters. More engineering projects in China are affected by unstable slopes, which require monitoring of slope displacement and loss of slope stability. Although the inherent mechanism of deformation and failure of landslide of different nature may be different, the inherent nature of shear failure is invariable.

The response of landslide deformation to the natural environment is more sensitive, and the influence of environment on the slope is often reflected in the time-displacement monitoring curve. For example, Rainfall is one of the main factors that induce landslide. When the rainwater infiltrates into the slope body, the weight of the slope body increases, and the penetration force produced by the rainwater in the slope body increases the sliding force of the slope body, and the stability of the slope body will decrease; When the slip zone soil is invaded by rainwater, its mechanical strength will be significantly reduced, anti-sliding force decreases, landslide stability is reduced. The change of stability shows acceleration of deformation on the time-displacement curve. But the rainfall is seasonal. During rainy season, rainfall is more and deformation is accelerated. In the dry season, rainfall is less and slope deformation is stable. This alternating rainfall effect makes the time-displacement curve of the landslide change step by step. Typical such as the Three Gorges reservoir area Baishuihe landslide step deformation curve (Figure 1).

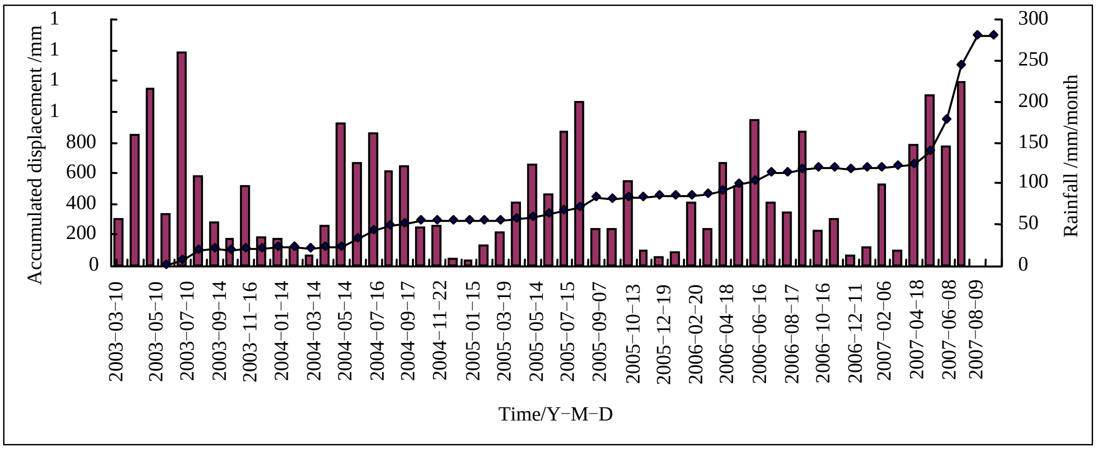


Fig.1 *Stepped deformation curve of Baishuihe landslide in Three Gorges reservoir*

There are two cases of shear failure of rock landslide, one is that the weak zone is thick, and the shear deformation is controlled by the property of weak layer, similar to that of soil landslide, and the intensity of slip belt is significant under rainwater intrusion And the deformation is accelerated, the shear deformation of the landslide changes with the seasons. The other is that there is no weak layer or thinner soft layer on the sliding surface, the shear deformation of the landslide is controlled by the sliding surface. According to Qin Si-Qing's locking theory [3], there are one or more locking sections in the sliding surface. When the sliding body breaks through a locking section, it may be unstable or may slide to another locking section. The process of breaking the locking section is the shearing failure process of the locking section, which accelerates when the locking section is sheared. When the shear process needs to cut a number of locking segments, the shear displacement curve should also be ladder-shaped.

Although the geomechanical model of soil and rock landslide is different, the shear deformation of the two is related to the sliding surface. According to Dieterich-Ruina friction law [4]: friction coefficient and sliding speed and sliding surface state. The deformation acceleration of the landslide deformation curve is caused by the change of the sliding surface. The change of the deformation rate of the landslide caused by rainfall is caused by the change of the physical properties of the sliding zone soil, while the rock landslide is caused by the change of the sliding surface due to the destruction of the locking section. Then for the same material with the physical and mechanical properties of the changes will inevitably lead to deformation characteristics of the change, and this change should be the same or similar. The deformation point of the time-displacement curve of the landslide and the velocity step point before the failure point should have certain similarity, or have certain proportion relation.

In order to verify the above point of view, the author chooses the rheological experiment to simulate the long-term deformation and failure process of the landslide. The shear failure process of landslide is the change of sliding force caused by the change of sliding surface. The rheological test results showed that the change of the shear stress caused by the graded loading caused the change of the sliding surface traits. Based on the velocity - reciprocal early warning model and the time - displacement data of the rheological test, the parameters of the early - warning model of the same material under the different working conditions and different load conditions are determined at the failure point and the velocity step point. If the parameters of the early warning model are distributed over a small range of values, it can be concluded that the failure point is similar to the deformation characteristic of the velocity step point.

3. Early - warning Model of Inverse-velocity Method:

The limit equilibrium method is often used to analyze landslide stability, but limit equilibrium method can't effectively deal with large and deep rock mass landslide, because limit equilibrium method can't consider long-term deformation process of landslide body. In 1961, Satio and Uezawa first predicted the failure time of landslide [5], fitted the relationship between time and deformation, and established the logarithm empirical formula of time and deformation rate:

$$\lg t_{\mathrm{f}} = c - m\lg V \qquad (1)$$

Where: t_f is the failure time; c and m are constant coefficients; V is the deformation rate.

Fukuzono [6] (1985) made important improvements to equation (1)Voight [7] [8] (1988,1989) through the static load in a pure shear process and the process of exponential creep analysis, the formula (1) was verified. The relationship between displacement acceleration and velocity is established.

$$V = AV^{a} \qquad (2)$$

Where: A, a, respectively, for the external conditions with time constant case. When a> 1, the time integral.

$$V = [A(a-1)(t_{\mathrm{f}} - t) + V_{\mathrm{f}}^{1-a}]^{1/(1-a)} \qquad (3)$$

Where: V_f is the rate of failure, its value can be fixed or infinite value. Equation (3) can be further simplified as:

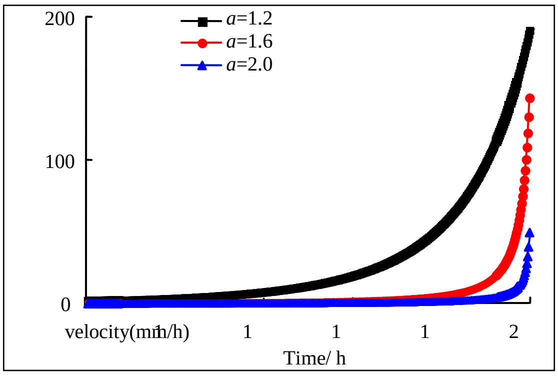
$$V = [A(a-1)(t_{\mathrm{f}} - t)]^{1/(1-a)} \qquad (4)$$

Or

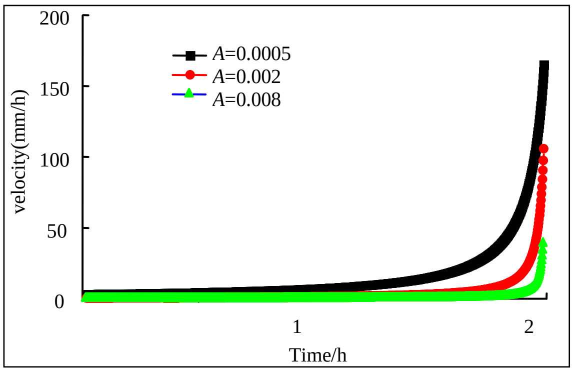
$$1/V = [A(a-1)(t_{\mathrm{f}} - t)]^{1/(a-1)} \qquad (5)$$

Where 'a' is a dimensionless quantity and is affected by the change in acceleration (Figure 2 (a)), A is a positive constant, affected by the shape of the curve (Figure 2 (b)), the smaller the A value, the smoother the curve; t is a time variable. 'A' and 'a' are properties of the material under static boundary conditions. Voight (1988, 1989) proposed a value range of 1.7 to 2.2, whereas Rose et al. [9] proposed a range of values from 1.5 to 2.2. A value of the above two documents are derived from the laboratory range, due to external factors, the actual value of a project may be beyond the range of values obtained by the laboratory.

When V $\rightarrow \infty$, the right t $\rightarrow$ t_f of the formula, when t = t_f, the landslide body instability. By establishing the relationship between the reciprocal of velocity and time, And use curve (5) to fit the curve, Find the value of A, a and tf into equation (5), Establish a forecasting model. Through the prediction model to calculate the deformation velocity warning value at different time points, this is the calculation process of the reciprocal velocity method.



(a) Effect of a on Curve Shape



(b) Effect of A on Curve Shape

Fig.2 *Model coefficients affect the curve shape*

4. Rheological test analysis

The soft rock is a kind of rock with low mechanical strength. It is easily affected by the external environment, especially water. Even without the impact of external environmental factors, due to its small stiffness, under the action of the force, the soft rock will occur to the surface of the plastic deformation.

4.1 Test design

A new type of direct shear rheological testing system is adopted in the experiment. The test equipment is stress-controlled direct shear apparatus. The system consists of testing machine, hydraulic station, six-channel high-precision hydraulic pressure regulator, load and displacement measurement system, computer data acquisition system.

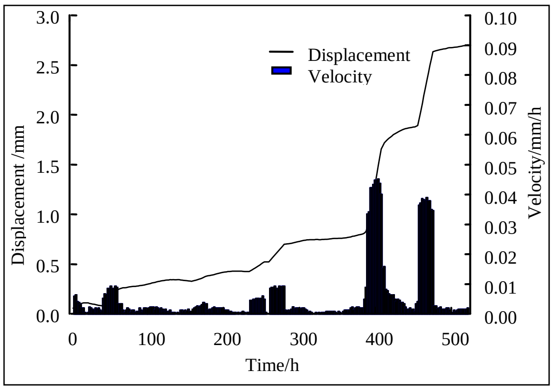
The shear area of specimen is 30 cm × 30 cm and the shear band is 12 mm. The specimen is taken from shear fracture zone. Specimen is divided into two working conditions: Natural samples, the normal stress were 0.3,0.4,0.5,1.2 MPa; water samples, the normal stress were 0.9,0.7,0.3,0.3 MPa, Shear stress The maximum shear stress obtained from the fast shear test is divided into seven stages. Each level of shear stress loading stress control method, the size of the normal stress of 5% to 10%.

4.2 Time - Displacement Curve under Different Loads

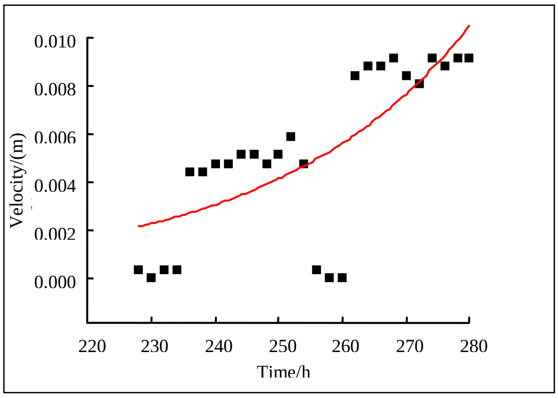
Four natural samples were added to the vertical load 0.3, 0.4 MPa, 0.5, 1.2 MPa, The sample numbers are shown in Table 1. The middle part of the rheological test curve of the natural sample has obvious velocity mutation point, the curve of TR-1 has a velocity step at t = 250 h, t = 400 h, t = 450 h (Fig. 3 (a)); the curve of TR-2 has a velocity step at t = 100 h, t = 320 h and t = 450 h (Fig. 4 (a)); The TR-3 test curve has a long creep deformation stage at the beginning of the test. The deformation mechanism is complex at this stage, so the speed mutation stage is not involved in the analysis. After the creep deformation, there is a velocity transition point at t = 100 h (Fig. 6 (a)), and the cumulative displacement is about 4 mm when the other specimen is destroyed. It is considered that this point is the failure point, the whole rheological deformation process and Duration is shorter. The TR-4 test curve has a velocity step at t = 150 h, t = 210 h, t = 350 h (Fig. 5 (a)). The characteristics of the test curves are similar to those of the landslide deformation monitoring curve (Fig. 1).

***Table 1**. List of sample load*

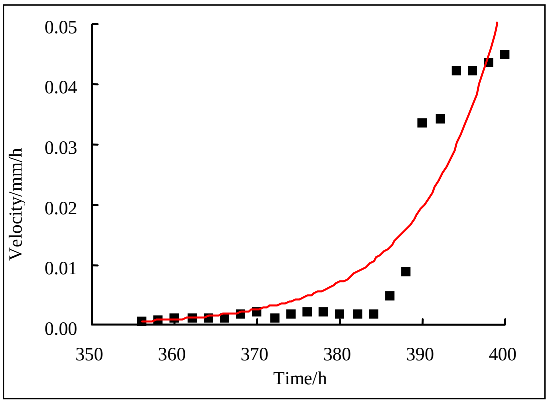
Sample number	TR-1	TR-2	TR-3	TR-4
Loading (MPa)	0.3	0.4	0.5	1.2



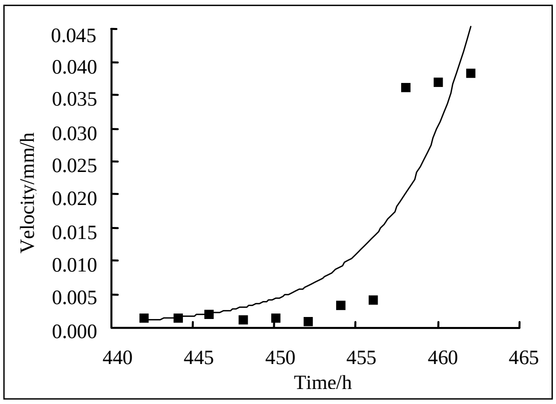
(a) Cumulative displacement and deformation velocity



(b) Velocity curve of t = 250h

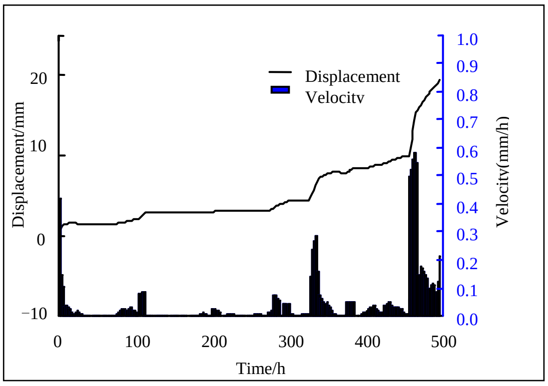


(c) Velocity curve of t = 400h

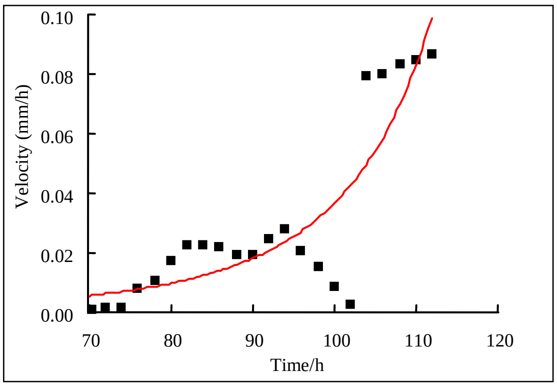


(d) Velocity curve of t = 450h

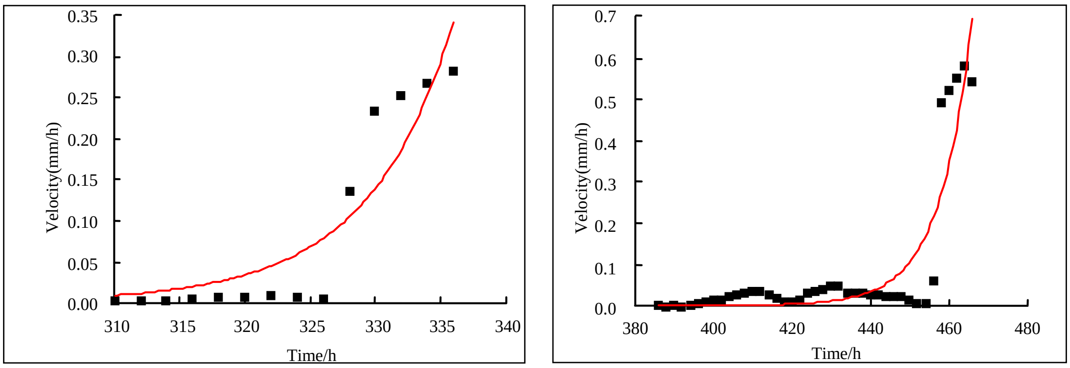
***Fig.3** TR-1 sample rheological experimental curve*



(a) Cumulative displacement and deformation velocity

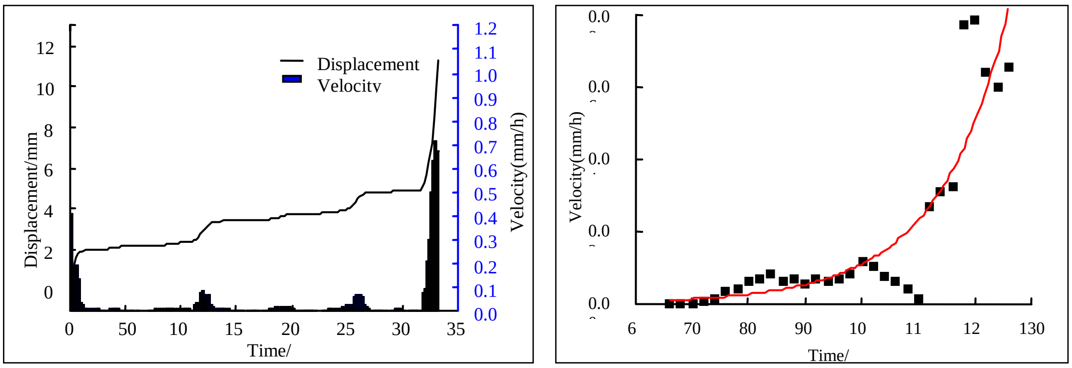


(b) Velocity curve of t = 100h

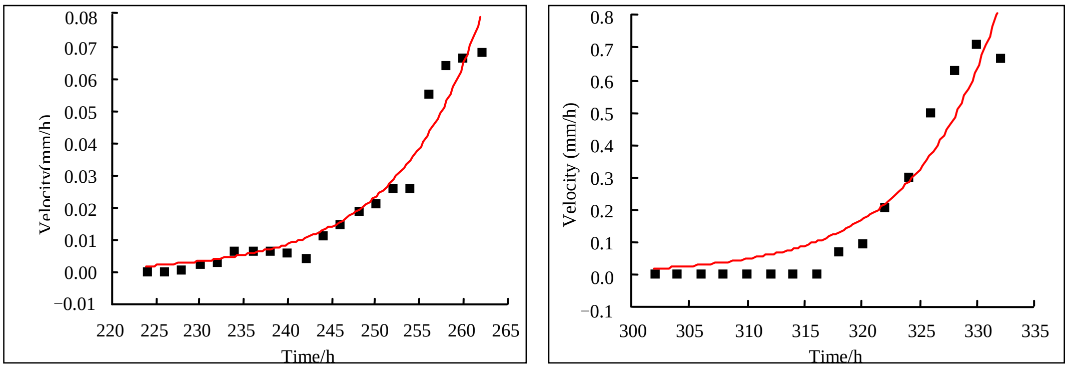


(c) Velocity curve of t = 320h *(d) Velocity curve of t = 450h*

***Fig.4** Sample TR-2 rheological experimental curve*

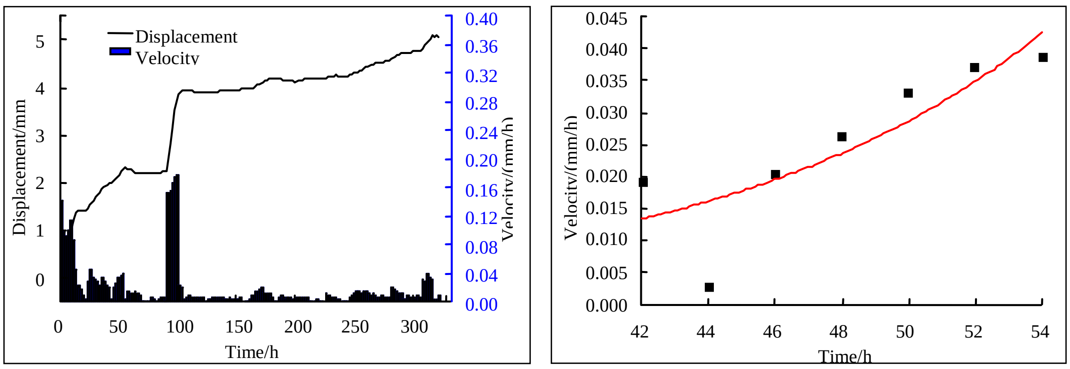


(a) Cumulative displacement and deformation velocity *(b) Velocity curve of t =150h*



(c) Velocity curve of t =210h *(d) Velocity curve of t =350h*

***Fig.5** Sample TR-4 rheological experimental curve*



(a) Cumulative displacement and deformation velocity *(b) Velocity curve of t =100h*

***Fig.6** Sample TR-3 rheological experimental curve*

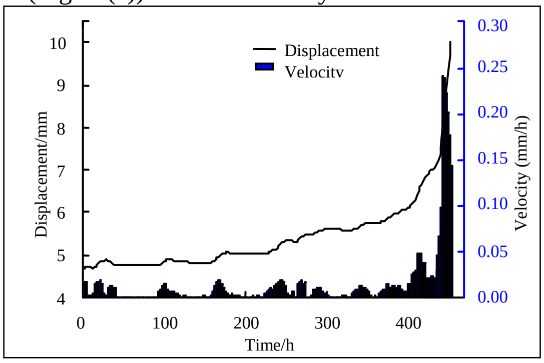
4.3 Time displacement curve under water immersion conditions

The load level of the immersion sample is 0.3,0.3,0.7,0.9 MPa, and the water content of the sample was measured. As a result, as shown in Table 2. Samples RL5-2 and RL5-5 were loaded with the same 0.3 MPa load, respectively, for the purpose of comparing the differences in the test curves for the same load and moisture content.

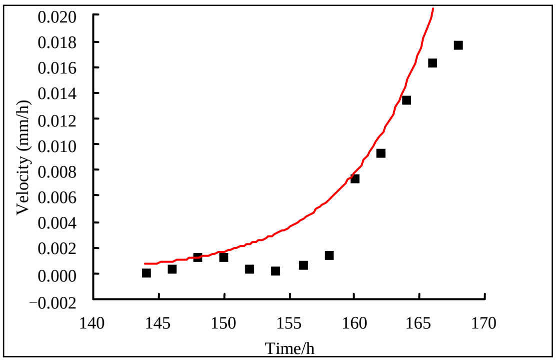
Table 2*. Load and moisture content of the test sample*

Sample No.	Water content /%	Loading/MPa
RL5-1	12.65	0.9
RL5-2	23.77	0.3
RL5-3	15.55	0.7
RL5-5	7.49	0.3

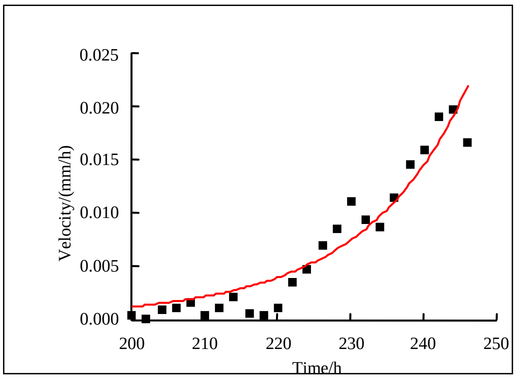
As shown in the figure, in the immersion test curve also has a speed mutation point. The deformation curve (Fig. 7 (a)) shows a velocity mutation at t = 160 h, t = 220 h, and t = 400 h, respectively, when the load is 0.9 MPa and the water content is 12.65%. Samples RL5-2 and RL5-5 were similarly loaded with 0.3 MPa. The RL5-2 specimen has a water content of 23.77%. In the time-displacement-velocity diagram (Fig. 9 (a)), the deformation rate is changed at t = 70 h and t = 180 h. The RL5-5 sample has a moisture content of 7.49%. In the time-displacement-rate diagram (Fig. 9 (d)), the deformation rate is suddenly changed at t = 135 h and t = 170 h. The specimen with RL5-3 is loaded with 0.7 MPa and the moisture content is 15.55%. In the time-displacement-velocity diagram (Fig. 8 (b)), the specimen is destroyed at t = 150 h.



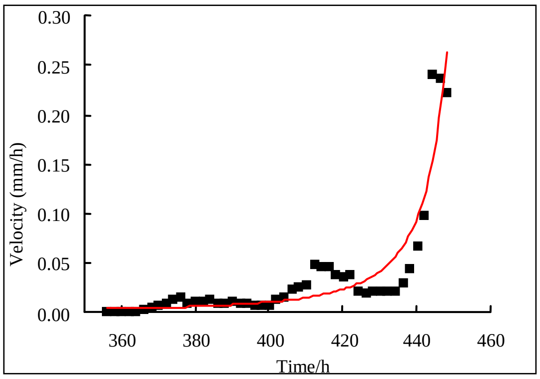
(a) Cumulative displacement and deformation velocity



(b) Velocity curve of t =160h

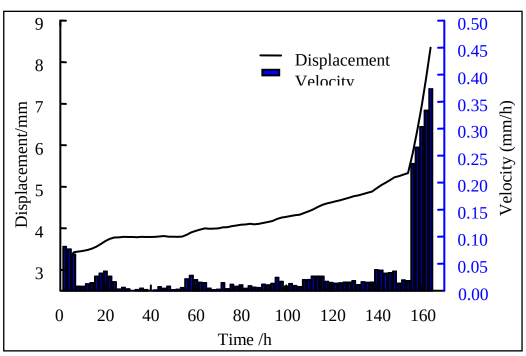


(c) Velocity curve of t=220h

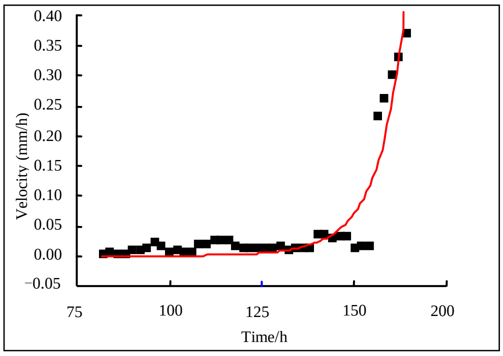


(d) Velocity curve of t=400h

Fig.7 *Sample No. RL5-1 rheological experimental curve*

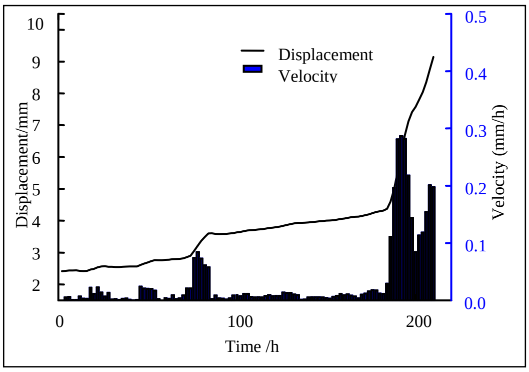


(a) Cumulative displacement and deformation velocity

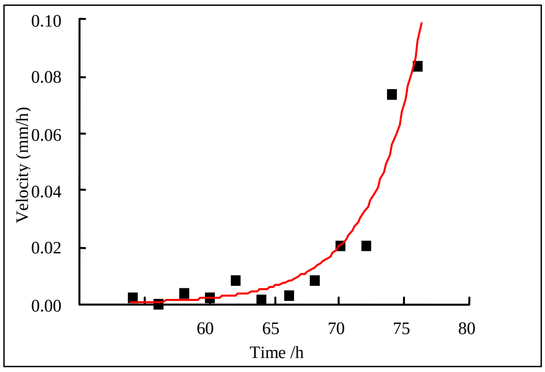


(b) Velocity curve of t=150h

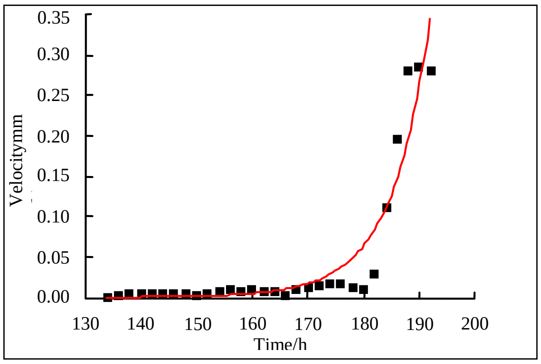
Fig.8 *Sample No. RL5-3 rheological experimental curve*



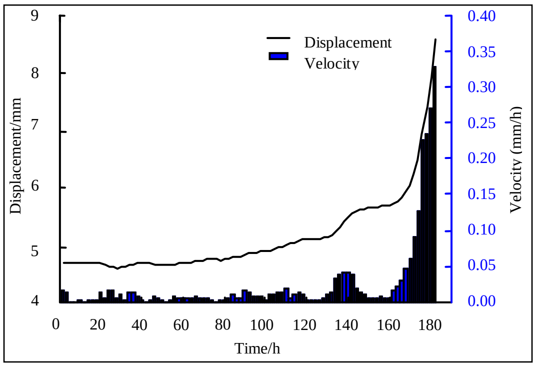
(a) Cumulative displacement and deformation velocity



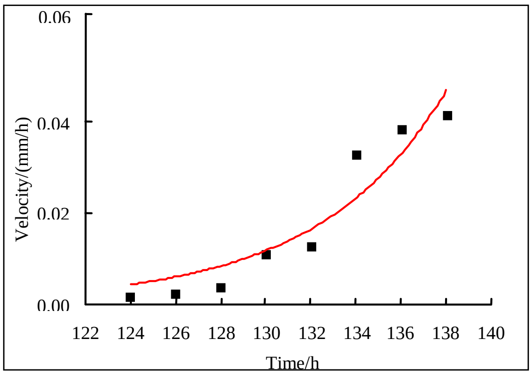
(b) Velocity curve of t=70h



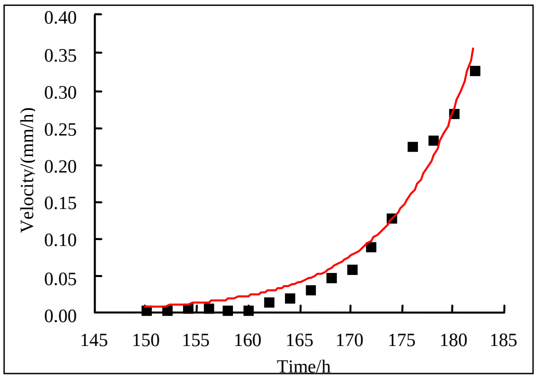
(c) Velocity curve of t=180h



(d) Cumulative displacement and deformation velocity



(e) Velocity curve of t=135h



(f) Velocity curve of t=170h

Fig.9 *Sample No. RL5-2 (Figures (a)-(c)) and Sample No. RL5-5 (Figures (d)-(f)) rheological experimental curve*

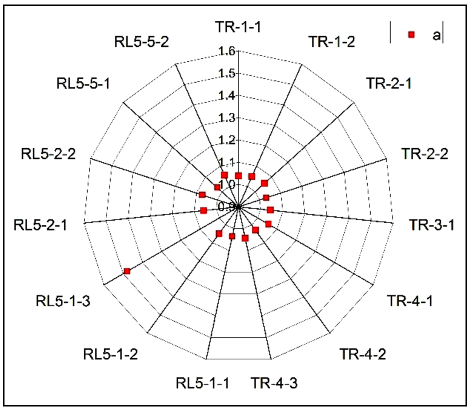
4.4 Test data analysis

According to the time-displacement-velocity curve obtained by the experiment, the model parameter values are determined according to the speed reversal method early-warning model for all the speed mutation points in the accelerated acceleration deformation stage (Natural sample curve, as shown in Fig3(b)～3(d)、4(b)～4(d)、5(b)～5(d)、6(b), And immersion specimens, as shown in Fig7(b)～7(d)、8(b)、9(b)、9(c)、9(e)、9(f).).

Since most of the time-displacement-velocity curves of the sample have more than two point mutations, the abrupt changes in velocity for each sample are numbered sequentially from time to time. Statistical Analysis Model Parameters (Figure 10). Exponential parameter a value range of basic distribution in the 1.0 to 1.1 between, values falls in the range of the probability of 93.3%. The mean value of a is 1.075 and the variance is 0.1085. The sample has a mutation value of 1.47888, which is not representative and belongs to a small probability event that can be ignored. Model coefficient parameter A value data is relatively scattered, the data are mainly distributed in the 0.1 ~ 0.2 interval, fall in the range of probability is 66.7%; the probability of falling in the range of 0.2 to 0.3 is 20%; the probability in the range of 0.05 to 0.1 is 13.3%. The average value of model A is 0.15649, and the variance is 0.0686. Analysis of the values outside the interval, one of which is a value corresponding to the abrupt value of a. The other two values occurred at the first velocity transition point of the experimental curve. One of the values is smaller than the interval value, and the other value is larger than the interval value. There is no regularity.

Table 3. *Test curve point mutation rate model parameters*

Numbering	parameters *a*	Parameters *A*	Correlation coefficient *R*
TR-1-1	1.03909	0.11945	0.84696
TR-1-2	1.04867	0.24376	0.75994
TR-1-3	1.05687	0.16288	0.80985
TR-2-1	1.03103	0.12328	0.80701
TR-2-2	1.04398	0.11446	0.58507
TR-2-3	1.05529	0.09326	0.79861
TR-3-1	1.03015	0.11201	0.93919
TR-4-1	1.04343	0.13952	0.89011
TR-4-2	1.03605	0.18745	0.90395
TR-4-3	1.04924	0.08388	0.89957
RL5-1-1	1.47888	0.31302	0.8349
RL5-1-2	1.05871	0.30155	0.90922
RL5-1-3	1.07201	0.14353	0.88072
RL5-2-1	1.02893	0.19344	0.85495
RL5-2-2	1.05561	0.14212	0.9562
RL5-5-1	1.03909	0.11945	0.84696
RL5-5-2	1.04867	0.24376	0.75994



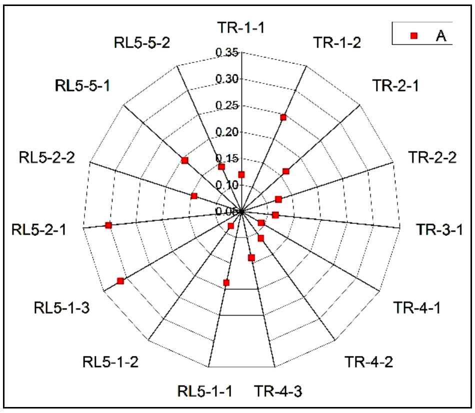


Fig.10 *Distribution of parameter values*

In practical engineering, the long-term monitoring curve of landslide is influenced by the external environment or its own sliding surface morphology, and the curve shape is often stepped. The rheological experiment also has similar characteristics by the graded loading of rheological test curves. It is well known that the sliding surfaces of a landslide or a rock specimen are not smooth but are undulating. Then the shear sliding process in the microscopic conditions, the upper and lower sliding surface in the sliding interaction between the two results are usually: over or cut. Cao et al (2013) [10] pointed out that under different load conditions, the shear surface of the high degree of ups and downs of different areas of shear failure, Load small shear area is small, large shear load area. This conclusion also confirms the nature of shear slip. According to the general rule of shear failure of rock mechanics, the deformation characteristics of similar materials under similar conditions are similar. According to this argument, the velocity step point of the rheological test curve should be similar to the deformation characteristic of the failure point, and the parameters of the early warning model calculated from the deformation should be similar. In this paper, the range of the early warning model parameters determined by the rheological experiment is distributed in a small range, which verifies the above viewpoints.

5. Conclusion

Through the above discussion, Voight's "velocity reciprocal method" landslide forecasting model, in the rheological test curve analysis can draw several conclusions:

(1) In soft rock, under different loading conditions, the velocity step point of the deformation curve and the velocity model of the failure point are consistent, and the change of the load does not affect the model parameters.

(2) Under the condition of water immersion, the velocity step point of the test curve under different load, different moisture content and same load, different water cut rate is close to the early warning model parameter of the failure point. It is shown that the change of water content and load has no effect on the model parameters.

(3) The deformation curve of the landslide is characterized by stepped deformation, and the early warning model parameters obtained by the early step point can be used to predict the damage point.

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