Original article
UDK: 626.01:632.125

RESEARCH ON PHYSICAL MONITORING AND WARNING PARAMETER AND INSTABILITY CRITERIA OF COLLUVIAL LANDSLIDE INDUCED BY RAINFALL

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Abstract. The stability analysis and evaluation of landslides is the foundation of the field of landslide geological disaster prevention and mitigation. Its stability evaluation method is the prerequisite for completing the stability analysis and evaluation landslides. In this paper, on the basis of systematic analysis of the change law of colluvial landslide displacement and rainfall and their interaction relationship, the basic principle of Elasticity and Plasticity is applied, and the rainfall is proposed as the dynamic parameter of landslide load. The corresponding landslide displacement rate or displacement acceleration change is used as the stability displacement response parameter, and the dynamic incremental displacement response ratio physical evaluation parameter and prediction model are established and determined. In addition, based on the principle of damage mechanics, a unified and stable physical stability monitoring and warning criterion with equivalent evaluation function with the safety coefficient of limit equilibrium method is established. Then, the dynamic incremental displacement response ratio prediction model is used to study the destabilization law of the Xintan landslide for example. The results indicate that the dynamic incremental displacement response ratio parameter is an effective physical monitoring and early warning and evaluation parameter for this type of landslide. It can be used to evaluate and predict the stability of colluvial landslide induced by rainfall.

Key words: *colluvial landslide; physical monitoring; instability criteria; rainfall.*

For citation: Keqiang H., Linna S., Lu G. *et al*. Research on physical monitoring and warning parameter and instability criteria of colluvial landslide induced by rainfall. *Journal of Science and Education of North-West Russia*. 2023. V.9. No. 1, pp. 37–55.

Научная статья
УДК: 626.01:632.125

ИССЛЕДОВАНИЕ ПАРАМЕТРОВ ФИЗИЧЕСКОГО МОНИТОРИНГА, ПРЕДУПРЕЖДЕНИЯ И КРИТЕРИЕВ НЕСТАБИЛЬНОСТИ КОЛЛЮВИАЛЬНОГО ОПОЛЗНЯ, ВЫЗВАННОГО ОСАДКАМИ

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Аннотация. Анализ и оценка устойчивости оползней является основой в области профилактики бедствий геологического характера и уменьшения ущерб от стихийных бедствий и предотвращения стихийных бедствий, а метод оценки устойчивости является предпосылкой для завершения анализа и оценки устойчивости оползней. На основе систематического анализа закона смещения оползня и изменения осадков и отношения их взаимодействия в аккумулятивных образованиях, в данной статье используются основные принципы механики упругопластичности, мы предлагаем принять количество осадков или приращение количества осадков в качестве параметра увеличений нагрузки оползня и соответствующую скорость смещения оползня или изменение ускорения смещения в качестве параметра реакции на смещение устойчивости, тем самым устанавливаются параметр физической оценки и модель прогнозирования коэффициента увеличений нагрузки реакции на смещение оползня аккумулятивного образования типа осадков; Кроме того, на основе принципа механики повреждений был установлен единый и стабильный критерий мониторинга физической устойчивости и предварительного предупреждения, который эквивалентен коэффициенту безопасности метода предельного равновесия. Оползень также углубленно изучается на примере модели прогнозирования коэффициента отклика динамического приращения нагрузки. Взяв в качестве примера оползень в Синьтане, углубленное исследование модели неустойчивости смещения оползня было проведено с помощью модели прогнозирования коэффициента реакции смещения с увеличением динамической нагрузки. Результаты исследования показали, что параметр отношения смещения увеличений нагрузки является эффективным параметром физического мониторинга и предварительного предупреждения для данного типа оползней, и может быть использован для оценки и прогнозирования устойчивости оползней аккумулятивного образования типа осадков.

Ключевые слова: *коллювиальный оползень; физический мониторинг; критерии нестабильности; дождевые осадки.*

Для цитирования: Кэцян Х., Линна С., Лу Г. и др. Исследование параметров физического мониторинга, предупреждения и критериев нестабильности коллювиального оползня, вызванного осадками // Вестник науки и образования Северо-Запада России. 2023. Т.9. № 1. С. 37-55.

1 Introduction

Landslide is a kind of frequent and serious geological hazard with strong suddenness and destructiveness, which poses a great threat to public safety and people's life and property in China. In the past 10 years, landslides have caused an average of 325 deaths and disappearances in China each year, and the economic loss has reached RMB 4.391 billion each year [1]. With the rapid development of society and economy, the number of large projects built gradually increases, and the scale and frequency of landslide hazards also show a trend of gradual enhancement. A large number of facts and studies have shown that the climate with abundant and heavy rainfall is the main factor to induce landslide hazards [2-4]. Especially in the evolution of colluvial landslides, rainfall undoubtedly plays an important role in triggering. Since the colluvial landslide is a type of landslide of the Quaternary and recent loose accumulation, it is decided that rainfall is the most important motive for the destabilization of this type of landslide. More than 94% of the instability in colluvial landslides is statistically caused by rainfall [5]. This indicates that the dynamic action caused by rainfall is the root cause of this kind of landslide hazards. Therefore, it is of great theoretical significance and practical application to study the relationship and mechanism of rainfall and colluvial landslide and to establish a prediction and forecasting method that is suitable for the dynamic action law and formation mechanism of this kind of landslide.

At present, the most important evaluation and prediction methods used for the stability of colluvial landslide induced by rainfall can be divided into the following two categories. One is the limit equilibrium method, which is based on porous flow calculations to determine the infiltration and pore water pressure distribution of the soil, and the evaluation of stability by applying the limit equilibrium method. Second, the time-series statistical prediction model is based on displacement monitoring, that is, based on the observation of displacement, atmospheric rainfall, and groundwater level. The time-series correspondence of rainfall, rainfall intensity, and groundwater with landslide displacement and its destabilization is studied. The time-series statistical prediction model of landslide displacement with rainfall and groundwater is established. Among them, the limit equilibrium method is a static evaluation model without considering the time factor, which is more suitable for static stability analysis and evaluation of colluvial landslide, but cannot effectively analyze and evaluate the dynamic stability of this kind of landslide with the time change and monitor and warn. However, the displacement time series prediction method is a method to evaluate and predict the stability of slope by observing the displacement-time change curve based on creep theory. This type of method takes the slope displacement as a monitoring and warning parameter. It analyzes its displacement change trend with time to evaluate the slope stability and predict its destabilization and damage time. Therefore, this type of model is a dynamic landslide prediction model that includes time-varying relationships. Because of the convenience of displacement monitoring and high calculation accuracy, this type of method has become a research hotspot in the field of slope stability evaluation and prediction. Since the Japanese scholar Saito (1969) [6], proposed the "Saito model", many scholars at home and abroad have been searching for landslide displacement dynamic laws and landslide stability prediction methods and have established a large number of landslide prediction models. In summary, there are three types of forecasting models. 1) statistical analysis forecasting models [7-12]; 2) nonlinear forecasting models [13-18]; and 3) integrated forecasting and multi-source information forecasting models [19-23]. Based on the research of landslide forecasting models, some scholars have proposed a series of slide instability criteria with certain applicability. For example, plastic strain rate criterion [24], fractional dimensional value criterion [25] two-parameter criterion of displacement rate and displacement vector angle [26], maximum acceleration criterion [27], creeping slip displacement dynamic stability criterion [28], vertical displacement directional rate criterion [29], and displacement ratio criterion [30]. The above-mentioned slope displacement prediction models and destabilization criteria have undergone the development process from empirical to theoretical, from qualitative to quantitative, from single evaluation to comprehensive evaluation. They have played a great role in the evaluation of the stability of slope. However, there are no uniform instability criterion for the displacement prediction parameters based on this type of method (Table 1). The critical displacement parameters vary significantly depending on the scale, boundary, dynamics, and other conditions of the landslide (Figure 1). Thus, it is impossible to make an accurate prediction of landslide occurrence time based on the instability criterion of this kind of method.

To address the shortcomings and limitations of the above-mentioned traditional landslide prediction parameters and models, on the basis of systematically determining the cause of landslide displacement instability and catastrophe mechanism and making full use of displacement and rainfall monitoring data, the hydrodynamic and displacement responses of landslides are organically coupled and integrated by using nonlinear scientific theory and modern mathematical and mechanical methods. Then, the physical monitoring and warning parameter and model are established to reflect and reveal the hydrodynamic catastrophe mechanism, and a unified and stable stability physical monitoring and warning criterion is established based on the principle of damage mechanics, which has equivalent evaluation function with the safety factor of limit equilibrium method.

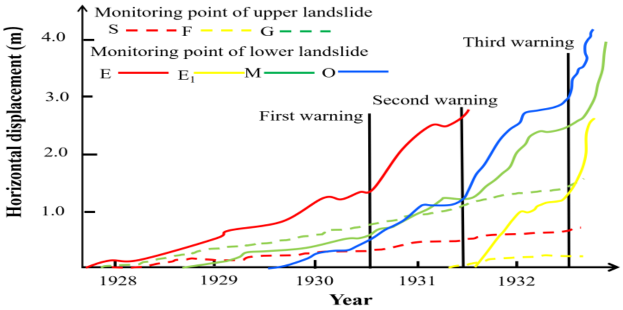

Figure 1 – The typical deformation graph of a landslide forecast failure case

Table 1 – The displacement velocity of some major typical landslides before sliding at home and abroad

The name of the landslide	The volume of the glide body /$10^4 m^3$	The slope displacement velocity before the sliding destruction （mm/d）
Sabujiang No.1 landslide (China)	0.75	7
Sabujiang No.2 landslide (China)	5.6	10
Lijiahe landslide of Baocheng line (China)	30	8.2
No.377 landslide of Chengkun line (China)	1.39	10
Vai aung landslide (Italy)	25000	800
Baihuichang landslide (China)	500	100
Yanchihe landslide (China)	100	1008
Dazhongchuandi landslide (Japan)	—	24
Dazhi iron mine’s landslide (China)	7	1000
No.1 landslide of the north Lion Rock (China)	16	29

2 Discussion on physical prediction parameter of dynamic incremental displacement response ratio and its feasibility

The process of landslide formation and development contains a series of links such as the formation, extension, connectivity, and dislocation of slip surfaces. In essence, the process is a sudden destabilization of the slope caused by the accumulation of relative displacements of the rock-soil mass units within the slope due to the continuous action of external forces to a certain extent. From the macroscopic point of view, due to the action of external forces, the rock-soil mass at the sliding surface is gradually damaged, and the intensification and accumulation of this damage will suddenly cause the destabilization of the slope after reaching a certain scale. Therefore, the study of landslide stress deformation and stability evolution law should take the rock-soil mass as the stress unit and analyze its stress-strain relationship and deformation and damage law.

2.1 Dynamic incremental displacement response rate parameter and its variation characteristics

From the intrinsic structure curve of the rock-soil mass (Figure 2), it can be seen that the stress-strain curve of the rock-soil mass unit under triaxial tensile and compressive conditions goes through the following stages. 1) The unit is in compression deformation in the OA stage, and the stress-strain curve is roughly a straight line. In this stage, almost no plastic deformation occurs. After a round of loading and unloading processes, the unit can basically recover its original state. 2) When the external force continues to increase, the stress-strain curve of the rock-soil mass unit enters the AB stage, that is, the elastic deformation stage. At this stage, the stress-strain curve is a straight line, and no plastic deformation is generated at this stage. After a round of loading and unloading process, the unit can fully recover its original state. In this stage, the strain is proportional to the change of stress $\Delta\varepsilon$ and $\Delta\sigma$, and the proportionality coefficient is λ; 3) As the external force continues to increase, the unit starts to produce plastic deformation when it enters the BC stage, and the stress-strain curve shows an upward convex shape. The change of stress $\Delta\sigma$ is nonlinearly related to the change of strain $\Delta\varepsilon$. If the ratio of strain change $\Delta\varepsilon$ to the stress change $\Delta\sigma$ in this phase is λ, then λ it increases gradually as the stress increases; 4) As the external force increases further, the material damage of the stressed unit accumulates further, and when the stress increases to point D, the material is completely destroyed, and the λ will tend to infinity.

The stress-strain curve and damage law of the rock-soil mass unit show that, as a nonlinear system, the proportional coefficient λ of the strain change $\Delta\varepsilon$ to the stress change $\Delta\sigma$ can be used as a quantitative representation of the stability state and the approach to instability before the material is completely destabilized and damaged, so the proportional coefficient λ is defined as the dynamic incremental displacement response rate. The mathematical expression is:

$$\lambda = \frac{\Delta\varepsilon}{\Delta\sigma} \tag{1}$$

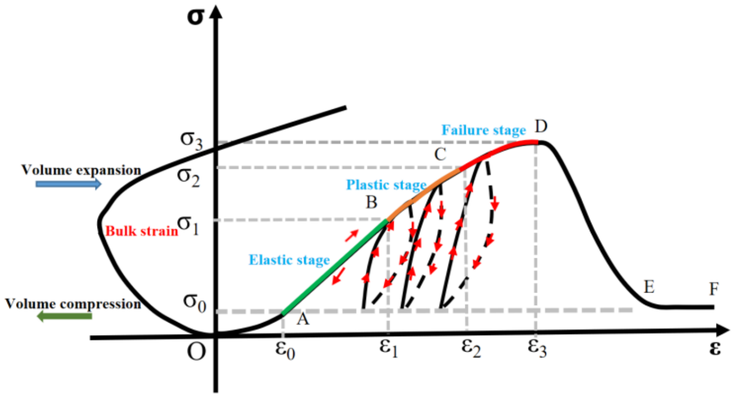

Figure 2 – Typical constitutive curves under triaxial stresses

Eq. (1) describes the degree of response of nonlinear system strain to stress changes under the action of external forces. Even if the applied load is constant, the degree of system response varies with its own steady state. As a typical nonlinear system, the slope is subjected to many external factors during its development, such as rainfall, groundwater, human factors, etc. After the slope body is subjected to these external forces, it will produce response results such as strain and displacement. Therefore, in the process of slope stability study, the above external forces can be noted as the generalized load P on the slope. The system response produced by the slope body after being subjected to the generalized load is R. Let the change in the generalized load on the landslide be ΔP, and the change in response to the load be ΔR, then the dynamic incremental displacement response rate λ of the system due to the load can be quantified as:

$$\lambda = \frac{\Delta R}{\Delta P} \tag{2}$$

For the monotonic load-increasing dynamic system, λ_t is the dynamic incremental displacement response rate at the moment t, λ_0 is the dynamic incremental displacement response rate during the initial deformation phase.

$$\lambda_t = \frac{\Delta R_t}{\Delta P_t} \tag{3}$$

$$\lambda_0 = \frac{\Delta R_0}{\Delta P_0} \tag{4}$$

The relationship between load and response in the evolution of slope stability can be obtained from the stress-strain curve of the rock-soil mass, as shown in Figure 3. According to the curve of dynamic incremental displacement response rate in the process of slope evolution, the slope can be divided into three stages from loading to instability damage as follows:

(1) When the system is in the stable stage, the dynamic incremental displacement response rate at the moment t is equal to the dynamic incremental displacement response rate during the initial deformation phase, i.e., $\lambda_t=\lambda_0$.

(2) When the system is in the plastic unstable stage, the dynamic incremental displacement response rate at the moment t is greater than the dynamic incremental displacement response rate during the initial deformation phase, i.e., $\lambda_t>\lambda_0$.

(3) When the system is in the instability stage, the dynamic incremental displacement response rate $\lambda_t\to\infty$.

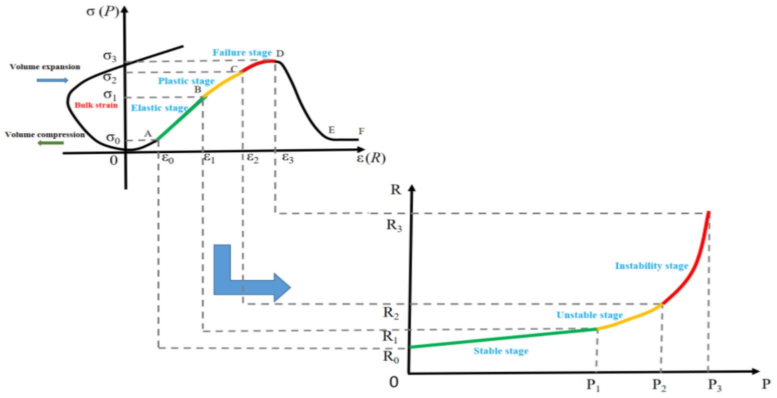

Figure 3 – Relationship between load and response in the process of landslide evolution

2.2 The characteristics of dynamic incremental displacement response ratio parameter and stability change law

In order to apply the dynamic incremental displacement response rate to the evaluation and prediction of landslide stability, it is necessary to extract a universal non-dimensional stability evaluation parameter based on the dynamic incremental displacement response rate. Therefore, in this paper, the dynamic incremental displacement response ratio is defined as the ratio of its dynamic incremental displacement response rate at the moment t, λ_t, to its dynamic incremental displacement response rate during the initial deformation phase, λ_0, whose mathematical expression is:

$$\eta = \frac{\lambda_t}{\lambda_0} = \frac{\Delta\varepsilon_t/\Delta\sigma_t}{\Delta\varepsilon_0/\Delta\sigma_0} = \frac{\Delta R_t/\Delta P_t}{\Delta R_0/\Delta P_0} \tag{5}$$

Where ΔR_t is the loading response increment at the moment t; ΔR_o is the loading response increment at the initial deformation stage; ΔP_t is the loading increment at the moment t, ΔP_o is the loading increment at the initial deformation stage.

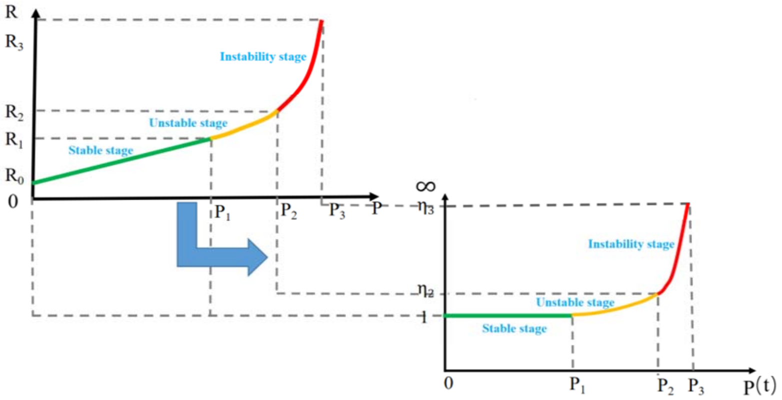

Figure 4 – Variation curve of dynamic incremental displacement response ratio in the process of slope evolution

From the definition of the dynamic incremental displacement response ratio parameter and the relationship between load and response, the evolution law of the dynamic incremental displacement response ratio can be derived (Figure 4). From the dynamic incremental displacement response ratio curve, it can be seen that the value of the dynamic incremental displacement response ratio parameter (η) depends on the degree of stability of the nonlinear system. When the system is in the stable phase, $\eta = 1$; when the system is in the plastic unstable phase, $\eta > 1$, the degree of instability depends on the difference of the dynamic incremental displacement response ratio deviation from 1; when the system is in the instability phase, $\eta \to \infty$.

According to the above analysis, the dynamic incremental displacement response ratio parameter (η) is a coupled evaluation parameter of the displacement and dynamic response of the nonlinear system. Its change characteristics reflect the change law of its system stability, and it has a one-to-one correspondence with stability. Therefore, this parameter is a physical evaluation parameter that portrays and reflects the evolution of its stability. In addition, this parameter can effectively reveal the mechanism of nonlinear system stability. Its magnitude only depends on the system stability change and is only related to its stability change, but is not affected by the dynamic change. Hence, it has more prediction and forecasting function of system stability evolution and sudden change. Therefore, the stability of the slope can be quantitatively calculated by the dynamic incremental displacement response ratio parameter, and the stability evaluation and early warning of instability prediction of the slope can be carried out.

3 Physical prediction model of dynamic incremental displacement response ratio of colluvial landslide induced by rainfall

3.1 Analysis of groundwater level dynamic equation and displacement dynamic response law of colluvial landslide

According to the dynamic characteristics of colluvial landslide displacement and the relationship between landslide groundwater level and effective rainfall [31]. (Eq. (6)), the displacement dynamic equation of landslide can be expressed as [32] (Eq. (7)):

$$h_t = AX_a(t) + B \tag{6}$$

$$m_i \frac{\partial^2 X}{\partial t^2} + U \frac{\partial X}{\partial t} + KX = (AX_a(t) + B)[(\rho_s - \rho - 1 + \rho_w)L \sin\alpha + (\rho - \rho_s + 1)Ltg\varphi \cos\alpha] + L\rho h(\sin\alpha - \cos\alpha\, tg\varphi) - CL/\cos\alpha - R_{i+1} \tag{7}$$

Where: h_t is the groundwater level; m_i is the slope mass; U is the slope viscosity coefficient; K is the slope resistance coefficient; A and B are related to the rock-soil mass properties, $A>0$; $X_a(t)$ is the effective monthly rainfall; $\frac{\partial^2 X}{\partial t^2}$ is the displacement acceleration; $\frac{\partial X}{\partial t}$ is the displacement velocity; X is the displacement amount.

This displacement dynamic equation system describes the quantitative relationship and law of dynamic slope action and displacement response. The following understanding can be derived from Eq. (7): The displacement dynamics of colluvial landslide mainly depend on the changes of groundwater environment caused by rainfall. There is a one-to-one correspondence between landslide displacement and its effective rainfall. Therefore, the change of effective rainfall of landslide can be taken as the dynamic loading of this type of landslide, the change of the corresponding displacement (displacement rate or displacement acceleration) can be taken as the dynamic loading response of the landslide, based on which the dynamic incremental displacement response ratio parameter (η) of the landslide can be determined, and this parameter can be used to analyze and evaluate the stability of the landslide and its evolution law.

3.2 Physical prediction parameters and model of dynamic incremental displacement response ratio of colluvial landslide

The process of slope from stability to instability will experience a series of phenomena such as the slip surface's generation → expansion → penetration → dislocation. These processes have an interactive relationship not only at the microscopic scale but also at the macroscopic scale. Coupled with the combined effect of various external dynamic influences, they lead to great differences in the dynamic action mechanisms and deformation laws of landslides in different regions, types, and scales. Thus, when using the prediction parameters and models of dynamic incremental displacement response ratio for effective forecasting of landslides, three problems need to be solved: how to apply and perform dynamic loading on landslides, how to determine and quantify the parameters of landslide loading and its response, and how to determine the period of landslide loading and its response change.

For the above three problems, this paper determines the calculation steps of dynamic incremental displacement response ratio parameters according to the displacement dynamics action law of colluvial landslide and the characteristics of loading as follows: 1) Take the periodic variation of rainfall (j) and rainfall increment (Δj) as the parameter of landslide hydrodynamic loading; take the variation of slope displacement rate (v) or displacement acceleration (a) during loading as the parameter of slope dynamic response. 2) The difference between the monthly rainfall and the average annual rainfall or the positive or negative monthly rainfall increment is used as the discriminating criterion for loading, and the loading response rates are determined according to the loading intervals respectively. The statistical calculation method of landslide dynamic incremental displacement response ratio parameters is shown in Table 2.

Table 2 – Loading and its response parameter selection and calculation method

Parameter type	Dynamic loading parameters		Dynamic loading response parameters	
	Cyclic loading parameter	Initial loading parameter	Cyclic loading response parameter	Initial loading response parameter R_0

	P_k	P_o	R_k	
Load increment parameters	Δj_k	Δj_0	a_k	a_0
Statistical mean parameters	j_k	j_0	v_k	v_0
Load comprehensive parameters	i_k	i_0	u_k	u_0
Calculation method of loading and its response parameters	$\bar{P}_t = \frac{1}{t}\sum_{k=1}^{t} \bar{P}_k$		$\bar{R}_t = \frac{1}{t}\sum_{k=1}^{t} \bar{R}_k$	

Based on the above selection and calculation methods of loading and its response parameter, the physical prediction parameters and models of dynamic incremental displacement response ratio of rainfall landslide suitable for medium, long, short-term and imminent sliding prediction are established respectively.

☐Incremental prediction model:
$$\eta_t = \frac{\lambda_t}{\lambda_0} = \frac{\Delta R_t}{\Delta P_t} \Big/ \frac{\Delta R_0}{\Delta P_0} = \frac{\overline{a_k}}{\Delta \overline{j_k}} \Big/ \frac{\overline{a_0}}{\Delta \overline{j_0}} \tag{8}$$

☐Mean value prediction model:
$$\eta_t = \frac{\lambda_t}{\lambda_0} = \frac{\Delta R_t}{\Delta P_t} \Big/ \frac{\Delta R_0}{\Delta P_0} = \frac{\overline{v_k}}{\overline{j_k}} \Big/ \frac{\overline{v_0}}{j_0} \tag{9}$$

☐Integrated prediction model:
$$\eta_t = \frac{\lambda_t}{\lambda_0} = \frac{\Delta R_t}{\Delta P_t} \Big/ \frac{\Delta R_0}{\Delta P_0} = \frac{\overline{a_k}}{\overline{j_k}} \Big/ \frac{\overline{a_0}}{\overline{j_0}} \tag{10}$$

Where: $(k = 1、2、…、h)$ is the number of monitoring periods; $\bar{j}_k$ and $\Delta\bar{j}_k$ denote the average monthly rainfall and the average monthly rainfall increment; $\bar{v}_k$ and $\bar{a}_k$ denote the average monthly displacement rate and the average monthly acceleration for k monitoring period; $\bar{j}_0$ and $\Delta\bar{j}_0$ denote the average monthly rainfall and the average monthly rainfall increment respectively for the initial monitoring period; $\bar{v}_0$ and $\bar{a}_0$ denote the average monthly displacement rate and the average monthly acceleration for the initial monitoring period.

Among the dynamic incremental displacement response ratio prediction models established above, the incremental prediction model is applicable to short-term and impending slip forecasts; the mean prediction model is applicable to medium- and long-term forecasts; and the integrated prediction model is applicable to medium- and long-term, and short-term forecasts.

4 Instability criterion of dynamic incremental displacement response ratio of colluvial landslide

4.1 Quantitative relationship analysis of dynamic incremental displacement response ratio and slope stability coefficient

Damage mechanics expresses damage as the process of material deterioration under various combined effects. Under the action of various external loads, the rock and soil mass of the slope produces plastic deformation, which makes the stability of the slope decrease gradually. In different stages of slope damage, its dynamic incremental displacement response ratio shows different change patterns. Therefore, the dynamic incremental displacement response ratio parameter can be used to quantitatively describe the degree of slope material damage development and its stability evolution law on a macroscopic scale. Therefore, the damage variable parameter can be introduced to construct a functional relationship between the slope stability coefficient and the dynamic incremental displacement response ratio parameter.

Damage mechanics expresses the process of landslide incubation as a damaging process of the slope material and quantifies the damage process of the slope in terms of damage variables. The damage variable can be represented by the different elastic modulus of the slope material before and after damage, that is, the rate of change of the elastic modulus of the material [33]:

$$D_t = 1 - \frac{E_t}{E_0} \tag{11}$$

Where: E_0 is the modulus of elasticity in the initial state (undamaged), E_t is the modulus of elasticity subject to damage. When the material is undamaged, $E_t = E_0$, D_t =0; when the material is completely damaged, E_t=0 , D_t=1.

The dynamic incremental displacement response ratio is defined as the ratio of the dynamic incremental displacement response rate in any deformation phase to its dynamic incremental displacement response rate in the initial deformation phase:

$$\eta_t = \frac{\Delta\varepsilon_t}{\Delta\sigma_t} \bigg/ \frac{\Delta\varepsilon_0}{\Delta\sigma_0} = \frac{E_0}{E_t} \tag{12}$$

Therefore, Eq. (11) can also be expressed as:

$$D_t = 1 - \frac{E_t}{E_0} = 1 - \frac{1}{\eta_t} \tag{13}$$

From Eq. (13), if η_t =1, then D_t=0, the slope material is not damaged, and the slope can maintain stability; if $\eta_t \to \infty$, then D_t=1, the slope material is fully damaged, and the slope is destabilized, thus in $D \in (0,1)$, it can be considered that the slope material has produced different degrees of damage, from the above formula can be further derived:

$$\eta_{cr} = \frac{1}{1 - D_{cr}} \tag{14}$$

Where D_{cr} is the critical damage variable.

Eqs (11), (13), and (14) show that there is a quantitative one-to-one relationship between the dynamic incremental displacement response ratio η of the rock-soil mass and its damage variable D .

In the traditional slope stability evaluation method, the stability coefficient is usually calculated by using the limit equilibrium method, and this is used to measure the stability of the slope. Starting from the theory of damage mechanics, Zhang et al. [34] defined the slope safety factor as the ratio of the ultimate damage variable $D_{\lim}$ ($D_{\lim}$=1) to the critical damage variable D_{cr} :

$$K = \frac{D_{\lim}}{D_{\mathrm{cr}}} = \frac{1}{D_{\mathrm{cr}}} \tag{15}$$

From this, the slope stability coefficient can be defined as the ratio of the ultimate damage variable $D_{\lim}$ to the damage variable D_t at any moment of the slope, that is:

$$F_t = \frac{D_{\lim}}{D_t} \tag{16}$$

Where: D_t is the damage variable at the t moment, $D_{\lim}$ is the limit damage variable, and its value is taken as 1.

Combine Eqs (13),and (16) respectively, and eliminate the intermediate parameter damage variable, we can get the function relationship between the dynamic incremental displacement response ratio and its stability coefficient as:

$$\eta_t = \frac{F_t}{F_t - 1} \tag{17}$$

Eq. (17) shows that the dynamic incremental displacement response ratio has an inverse proportional function relationship with the stability coefficient. They correspond to each other in the definition domain. This indicates that the slope stability coefficient can be quantitatively related to the dynamic incremental displacement response ratio by applying the damage variables, thus realizing the quantitative description of the dynamic incremental displacement response ratio parameter for the degree of damage development of slope materials and its stability evolution law at the macroscopic level.

4.2 Stability criterion of dynamic incremental displacement response ratio based on slope safety factor and its application

The study of slope instability prediction is ultimately to make a reasonable evaluation and scientific prediction of its possibility of occurrence. At present, in the field of slope stability evaluation, it is still accepted and practical to use whether the actual stability coefficient of slope is greater than or equal to 1 or the degree of greater than 1 as the criterion for judging whether the slope is stable and the degree of stability. In the practical work of landslide control and its engineering survey and design, a safety reserve is usually set for the stability coefficient to get a safety factor K as the criterion of its stability or not, and its purpose is to consider a threshold value of the stability coefficient given by the importance of the project. Therefore, from Eq. (18), we can establish the stability criterion of dynamic incremental displacement response ratio based on the safety factor of slope:

$$\eta_{cr} = \frac{K}{K - 1} \tag{18}$$

In engineering practice, the minimum safety coefficient of the slope should be selected within the range specified in the standard specification, taking into account the grade of slope, application conditions, governance, and other factors. For example, the "Chinese Code for the design of slope of water conservancy and hydropower projects (SL386 - 2016)" stipulates that the grade of slope is divided into 5 grades [35], and the corresponding safety factors of different grades of slope are shown in Table 3. Since there is a one-to-one correspondence between the dynamic incremental displacement response ratio and the safety factor (Eq. (18)), the critical value of the dynamic incremental displacement response ratio can be used as the slope stability criterion value, as shown in Table 4. Therefore, according to the stability criterion of the dynamic incremental displacement response ratio, the stability of the slope can be analyzed and evaluated as follows: when $\eta \le \eta_{cr}$, the slope is in a relatively stable state; when $\eta > \eta_{cr}$, the slope is in an unstable state.

Table 3 – Safety factor division based on slope grade

Slope grade	1	2	3	4	5
Safety factor (*K*)	1.30~1.25	1.25~1.20	1.20~1.15	1.15~1.10	1.10~1.05

Table 4 – Dynamic incremental displacement response ratio criterion based on slope safety factor

Safety factor (*K*)	1.30	1.25	1.20	1.15	1.10	1.05
Critical value of dynamic incremental displacement response ratio (η_{cr})	4.33	5	6	7.67	11	21

5 Case study

5.1 Xintan landslide overview

Xintan landslide is located on the north bank of Yangtze River in Xintan Town, Zigui County, Yichang City, Hubei Province, about 27 km away from the Three Gorges Project with the slope spreading in a nearly north-south direction, narrow in the north and wide in the south. The elevation of the front edge is about 65 m, the elevation of the back edge is about 900 m, and the average slope of the slope is about 23°. The accumulation is generally 30~40 m thick, thickening from east to west, and the accumulation is dominated by crumbling debris interspersed with clay. At 3:45 a.m. on June 12, 1985, a high-speed giant colluvial landslide with a total volume of about 30 million cubic meters of soil and rocks occurred, and the Xintan landslide slid along the clay layer at the bottom of the accretion. The longitudinal geological section and the plane distribution of the basic monitoring points are shown in Figure 5 and Figure 6.

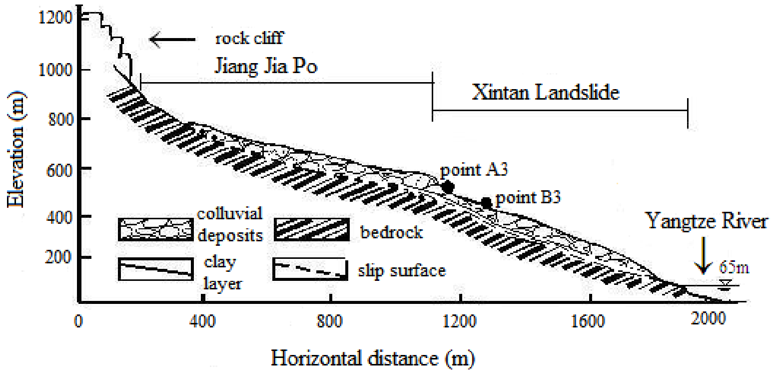

Figure 5 – The geological section of Xintan landslide [31]

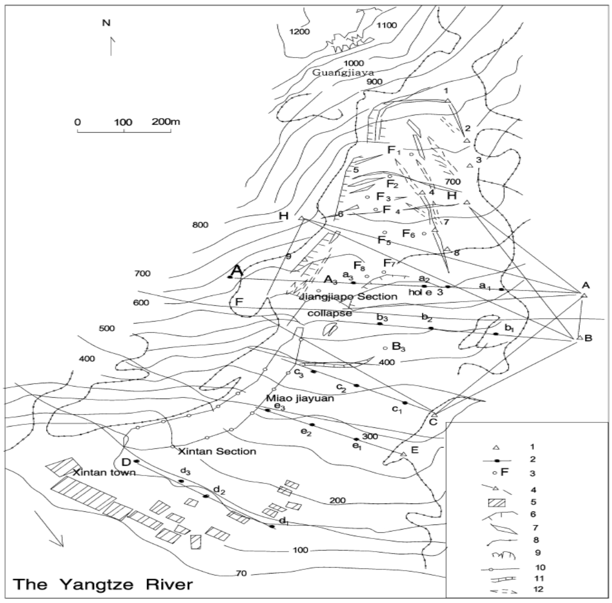

Figure 6 – Distribution of deformation observation points of Xintan landslide [31]:
1 - Control monitoring points; 2 - Monitoring lines and the points; 3 - Monitoring points for displacement; 4 - Simple monitoring points; 5 - Residential area; 6 - Cliff of falling rock-mass; 7 - The tensile fissures; 8 - Boundary line between Quaternary system and bedrock; 9 - Cliff; 10 - Boundary line of small scale slide before landslide; 11 - Bulging area; 12 - New ground fissures

The main reason for the development and resurgence of the Xintan landslide is rainwater infiltration. The landslide is located within the Three Gorges reservoir area, with an annual rainfall of 1100 mm/a, which is mostly concentrated in May-August and often accompanied by extreme rainfall. The surface water collected in the catchment area of the old landslide body (about 2 km^2) infiltrates into the landslide in large quantities, prompting the groundwater level to rise, increasing the pore water pressure and floating support force, and softening the slide zone soil on the top surface of the bedrock, reducing the effective stress and shear strength between the soil skeleton particles, and intensifying the development of landslide deformation.

5.2 Displacement prediction parameter time series curve characteristics and stability monitoring and early warning of Xintan landslide

In order to monitor and determine the deformation characteristics and evolution trend of Xintan landslide and to monitor the landslide displacement for a long time since 1978, the monthly rainfall monitoring data of the landslide area and the deformation pattern of monitoring points A3 and B3 at the leading edge of the main landslide area are shown in Tables 5, 6,7 and Figure 7.

Table 5 – The monthly rainfall data in Xintan landslide (Unit: mm)

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1978	30.4	7.6	58.4	95.1	224.6	154.2	61.9	35.7	62.5	55.2	54.0	12.9
1979	6.0	2.3	21.7	116.1	168.3	138.8	146.9	87.9	359.3	12.4	7.6	50.9
1980	18.2	20.5	76.3	38.7	99.1	292.5	250.9	281.3	85.7	67.3	21.3	0.3
1981	14.8	31.5	61.7	99.3	54.5	67.1	90.9	221.9	55.7	100.4	47.0	4.6
1982	19.7	18.1	86.4	86.1	87.6	170.0	189.7	137.8	159.8	78.4	75.3	4.1
1983	21.3	14.8	42.2	79.3	97.3	195.4	313.7	126.3	183.2	276.4	40.8	12.3
1984	19.0	2.6	39.4	65.4	103.1	243.2	99.9	108.3	154.2	80.2	54.2	47.6
1985	5.2	38.5	16.6	79.1	162.6	126.6	156.1	121.7	—	—	—	—

Table 6 –The monthly displacement rate of A3 in Xintan landslide (Unit: mm/ month)

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1978		3.2	7.1	6.1	6.4	8.7	13.1	6.9	4.8	1.8	1.8	7.5
1979	1.6	7.2	1.0	1.6	5.0	10.5	5.7	19.7	336.3	161.3	39.8	1.6
1980	14.3	11.1	7.8	4.2	9.7	9.7	80.8	49.5	59.5	20.7	9.4	18.7
1981	22.9	6.9	6.2	10.6	6.5	5.0	3.4	10.2	8.6	11.7	6.8	1.9
1982	8.2	7.5	6.8	33.2	66.7	82.2	54.5	344.2	430.6	525.6	433.5	35.3
1983	45.3	15.0	31.8	16.4	20.0	20.8	43.9	348.1	101.3	171.2	298.7	156.2
1984	69.1	51.3	27.6	15.5	49.0	127.9	196	320.1	136.1	413.8	325.8	214.6
1985	142.1	146.1	153.3	123.0	296.1	2005.9	—	—	—	—	—	—

Table 7–The monthly displacement rate of B3 in Xintan landslide (Unit: mm/ month)

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1978		3.4	3.8	4.3	4.0	14.6	17.1	6.0	8.5	2.6	0.2	10.0
1979	1.6	3.9	4.9	1.5	4.7	11.1	10.9	23.5	125.1	65.0	37.5	8.2
1980	15.2	9.9	4.6	9.0	5.0	15.0	49.0	68.0	100.0	1.7	31.7	8.1
1981	7.5	7.7	8.4	15.2	12.5	8.8	4.2	2.9	26.0	2.0	5.0	8.0
1982	5.0	3.5	7.5	78.0	148.6	21.6	21.5	136.2	250.8	243.0	75.8	71.5
1983	100.7	28.7	31.9	31.2	32.1	28.8	129.4	152.1	152.1	152.1	152.1	151.8
1984	152.4	152.1	152.1	152.1	152.1	152.1	237.7	333	151.8	522.1	271.7	237.7
1985	158.3	149.4	164.5	127.3	381.7	10102.6	—	—	—	—	—	—

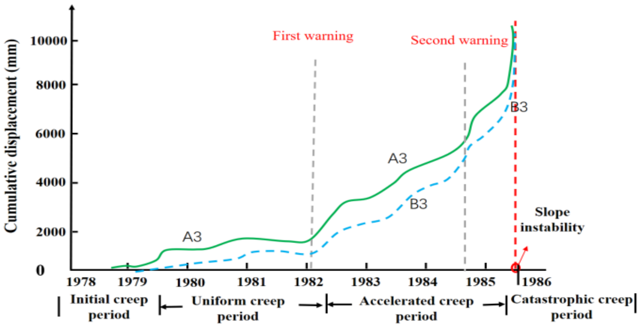

Figure 7 – Cumulative displacement variation curve of Xintan landslide

The cumulative displacement time series curves of the landslide in Figure 7 shows that the cumulative displacement values of A3 and B3, the key monitoring points of the landslide, have been increasing since Xintan landslide started monitoring in 1978. The cumulative displacement curve shows two accelerated deformations, and each strong displacement accelerated change seems to indicate that the landslide is about to be unstable. However, the slope has always remained stable. Therefore, only the sudden change of displacement time series curve is used as the judgment criterion of slope instability, which inevitably increases the risk of miscalculation or misjudgment of landslide.

5.3 Dynamic incremental displacement response ratio prediction parameter time series curve characteristics and stability monitoring and early warning of Xintan landslide

Based on the displacement and rainfall monitoring data of key monitoring points A3 and B3 of the Xintan landslide, this paper analyzes and evaluates the stability evolution law of this landslide based on the dynamic incremental displacement response ratio prediction model (Eq. (9)), using the statistical method of monthly displacement rate and monthly rainfall mean value. Since the rainfall in the Three Gorges area is relatively high from May to August each year. It is often accompanied by extreme and continuous rainfall. It is also a high landslide occurrence period. Therefore, in the data selection, the rainfall and displacement rate values in April of the first year were selected as the initial dynamic loading of the landslide and its corresponding dynamic loading displacement response parameters. The average value of monthly rainfall from May to August of each year was selected as the rainfall dynamic loading $\bar{J}$ of the landslide. The corresponding average value of monthly displacement rate was taken as the rainfall dynamic loading displacement response parameter $\bar{v}$, whose calculation results are shown in Table 8. And from Eq. (9), the corresponding dynamic incremental displacement response ratio η_t for this landslide monitoring points in different rainfall loading sections can be determined, and the calculation results are shown in Table 9. According to the Chinese code for Landslide Design of Water Conservancy and Hydropower Projects (SL386-2016) and Eq. (18), the safety factors of the yellow, orange, and red warnings of the landslide are 1.15, 1.10, and 1.05, respectively, which can determine the critical warning values of the dynamic incremental displacement response ratio corresponding to the yellow, orange and red warnings respectively as $\eta_{cr} = 7.67、11、21$, and the dynamic incremental displacement response ratio and stability anomaly criterion of the two monitoring points are shown in Figure 8.

Through the dynamic incremental displacement response ratio curves of A3 and B3 points in Figure 8, it can be seen that the landslide has been in a relatively stable state from 1978 to 1982. In other words, the dynamic incremental displacement response ratio fluctuates slightly upward with 1 as the base point, indicating that the landslide as a whole is in the evolutionary stage of stability and is basically stable. Still, there is a trend of gradually decreasing stability. During the period from 1982 to 1984, the dynamic incremental displacement response ratio of the landslide increased gradually, indicating that the landslide was in an unstable evolution stage and its stability gradually decreased, and in early 1985 both exceeded the dynamic incremental displacement response ratio stability orange critical warning value η_{cr}.

Table 8 – The monthly average rainfall and displacement rate in Xintan landslide during loading periods

Time	Jan.1979	Jan.1980	Jan.1981	Jan.1982	Jan.1983	Jan.1984	Jan.1985	Jun.1985
Mean monthly	119.100	135.475	230.950	108.600	146.275	183.175	138.625	144.600
Average monthly displacement rate of A3 monitoring point (mm/month)	8.775	10.225	37.425	6.275	136.900	108.200	173.250	1151.000
Average monthly displacement rate of B3 monitoring point (mm/month)	10.425	12.550	34.250	7.100	81.975	85.600	218.725	5242.150

Table 9 – Dynamic incremental displacement response ratio of monitoring points A3 and B3

Time	Jan.1979	Jan.1980	Jan.1981	Jan.1982	Jan.1983	Jan.1984	Jan.1985	Jun.1985
η_{A3}	1.149	1.164	1.812	1.645	4.203	5.196	7.060	21.084
η_{B3}	1.936	1.996	2.607	2.394	4.370	5.553	9.383	104.328

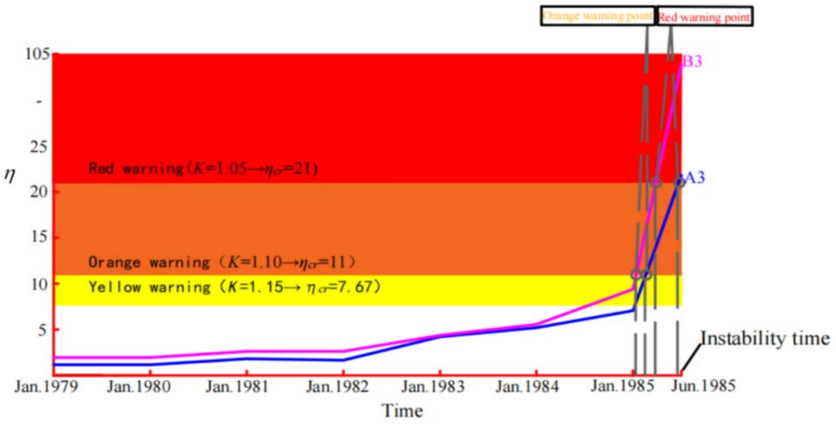

Figure 8 – Monitoring and early warning curve of dynamic incremental displacement response ratio at A3 and B3 monitoring points of Xintan landslide

Before the final landslide destabilized in June 1985, the dynamic incremental displacement response ratio of both monitoring points changed abruptly and were greater than the red critical warning value η_{cr} , and the red warning time was less than half a year away from the actual destabilization time of the landslide, indicating that the dynamic incremental displacement response ratio and its criterion have certain practicality and effectiveness in dynamic monitoring and warning of landslide stability.

Comparing the traditional displacement warning results (Figures 7, 8), it can be found that the dynamic incremental displacement response ratio parameter has stronger stability compared with the traditional displacement prediction parameter. However, it shows significant abrupt change characteristics and precursors of instability before destabilization, and its time-series change and abrupt change characteristics can better reflect the overall stability evolution law of landslide, and the abrupt change warning time basically matches with the actual destabilization time of the landslide. Thus, it shows that the stability evaluation and monitoring, and early warning of colluvial landslide can be carried out by using the dynamic incremental displacement response ratio parameter.

6 Conclusion

(1) According to the formation mechanism and the cause of instability of extreme rainfall colluvial landslides, the dynamic factors of such landslides are quantitatively coupled with the displacement response rule and the formation mechanism of landslides. The rainfall is proposed as the dynamic parameter of landslide load, and the corresponding landslide displacement rate or displacement acceleration change is used as the stability displacement response parameter. Based on this, the dynamic incremental displacement response ratio parameter and prediction model were established and determined. The prediction model can not only describe the causes and mechanisms of landslide stability evolution and displacement change, but also quantitatively monitor and evaluate the dynamic stability of landslide.

(2) Based on the basic principle of damage mechanics, the internal relation and one-to-one correspondence between dynamic incremental displacement response ratio, damage variable and stability coefficient of limit equilibrium method are revealed and established. A method of determining the stability coefficient of traditional limit equilibrium method by dynamic incremental displacement response ratio is established. Therefore, a new method is developed to determine the stability coefficient of limit equilibrium method by means of rainfall and displacement coupling monitoring.

(3) According to the engineering significance of landslide safety factor of limit equilibrium method, the monitoring and warning value of dynamic incremental displacement response ratio and the instability criterion are established by using the quantitative relationship between damage variable parameters of damage mechanics and dynamic incremental displacement response ratio. Taking Xintan landslide as an example, a posteriori analysis and evaluation of the stability of Xintan landslide are carried out by using dynamic incremental displacement response ratio parameter and prediction model. The results of analysis and evaluation are in good agreement with the actual stable state of landslide. This indicates that the dynamic incremental displacement response ratio is suitable for evaluating and monitoring the dynamic stability of colluvial landslides.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (41372297), the Natural Science Foundation of Shandong Province (ZR2020KE004).

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Статья поступила в редакцию 21.01.2023; одобрена после рецензирования 02.02.2023, принята к публикации 22.03.2023.
The article was submitted 21.01.2023; approved after reviewing 02.02.2023; accepted for publication 22.03.2023.