A landslide prediction model based on load-unload response ratio theory and its application

Un modelo de predicción de deslizamientos basado en la teoría del ratio de respuesta carga-descarga y su aplicación

Zhen Zhu[1,2], Xuchun Wang[2], Peng Zhang[2*] and Manchao He[1]

[1] State Key Laboratory for GeoMechanics and Deep Underground Engineering, China University of Mining and Technology, Beijing 100083, China
[2] School of Civil Engineering, Qingdao University of Technology, Qingdao 266033, China
[*] Corresponding author, e-mail: zhangpchn@qut.edu.cn

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RESUMEN

- Los deslizamientos de tierra son uno de los desastres geológicos más comunes que amenazan seriamente la producción y la vida humana. Por lo tanto, es de gran importancia predecir con precisión los desastres por deslizamientos de tierra. Sin embargo, el proceso de deslizamiento va acompañado de una serie de reacciones mecánicas extremadamente complejas, determinadas por diversos factores, como la resistencia de la roca y del suelo, la disposición y la estructura del estrato, las perturbaciones externas, etc., y estos factores son difíciles de captar con precisión. Para predecir el deslizamiento con precisión, se propuso un modelo integral de pronóstico de deslizamientos basado en la teoría del ratio de respuesta carga-descarga (LURR). En este modelo, se midió la fuerza de deslizamiento dentro de la pendiente y el desplazamiento de la superficie de la pendiente como parámetros clave. La fuerza de deslizamiento, como parámetro de carga y descarga, se obtuvo mediante un sistema de monitorización remota de perturbaciones de deslizamiento (SPRM)- Mientras que el desplazamiento, como parámetro de respuesta de carga y descarga, fue medido por la estación total. Además, la velocidad y la aceleración del desplazamiento también se utilizaron como parámetros para mejorar la precisión de la predicción del peligro de deslizamientos. El modelo de predicción de deslizamientos LURR se aplicó en las laderas a tajo abierto de Antaibao y Pingzhuang oeste. Los resultados muestran que el modelo propuesto es preciso y fiable para la predicción de deslizamientos. El modelo de acoplamiento de desplazamiento de fuerza es más eficiente en la predicción de deslizamientos y en la alerta temprana, lo cual es útil para rastrear las causas de los deslizamientos.
- **Palabras clave:** Predicción de deslizamientos, Ratio de respuesta carga/descarga, Fuerza de deslizamiento, Monitoreo remoto.

ABSTRACT

Landslide is one of the most common geological disasters that seriously threatens human production and life. Hence it is of great significance to accurately predict landslide disasters. However, the process of landslide is accompanied by a series of extremely complex mechanical reactions, which are determined by various factors, such as the strength of rock and soil, the attitude and structure of stratum, the external disturbances and so on, and these factors are difficult to accurately capture. To predict the landslide accurately, a comprehensive landslide forecast model was proposed based on the load-unload response ratio (LURR) theory. In this model, sliding force inside the slope and displacement of the slope surface as the key parameters were measured. The sliding force, as the load-unload parameter, was obtained by a sliding perturbation remote monitoring (SPRM) system. While the displacement, as the load-unload response parameter, was measured by total station. Besides, the velocity and acceleration of displacement were also used as parameters to improve the accuracy of landslide hazard prediction. The LURR landslide prediction model was applied in Antaibao and Pingzhuang west open-pit slopes. Results show that the proposed model is accurate and reliable for landslide prediction. The force-displacement coupling model is more efficient in landslide prediction and early-warning, which is helpful to track the causes of landslide.

Keywords: Landslide prediction, Load-unload response ratio, Sliding force, Remote monitoring.

1. INTRODUCTION

Landslide hazard is one of the repeated geological disasters during rainy season, which often causes fatalities, damages and economic losses [1-3]. The reliable and affordable instrumentations coupled with feasible early warning methods should be developed to provide an early warning of slope instability, and to ensure the safety of human lives, private property and public facilities [4-6].

In the past years, lots of theories and technologies of landslide prediction have been carried out [7-11]. In general, landslide prediction theories have gone through three stages, namely phenomenon forecast and empirical prediction stage, displacement-time analysis and prediction stage, and comprehensive forecast model and forecast criterion research stage. Landslide prediction based on the load-unload response ratio (LURR) theory belongs to the third stage.

The LURR is a theory proposed for precursor study and instability prediction of nonlinear systems, and it describes the deviation from stability status of a nonlinear system [12]. One of the instability precursors is the increasing difference between loading response and unloading response, which was primarily used to predict earthquake. Moreover, the ratio of loading response rate to unloading response rate can be used to depict the degree of deviation from stability and tendency to instability for a nonlinear system.

Therefore, a landslide prediction model based on LURR was proposed and it was verified in two open-pit slope engineerings in this study.

2. STATE OF THE ART

Landslide is a very common natural and geological disaster. Geologists and geotechnical engineers from all over the world, especially from countries beset by frequent landslide disasters, have made a lot of efforts to study the mechanism and space-time relationship of landslide occurrence in order to predict landslide disasters and mitigate the impact of such disasters on human beings[13-16]. In the initial stage of landslide prediction research, it is believed that the displacement and deformation of the slope have obvious stage characteristics before sliding, based on the creep and rheological properties of rocks or soils [17]. During this period, some landslide prediction models based on slope displacement, creep velocity or acceleration are proposed. In general, these prediction models determine the occurrence of landslides mainly according to the relationship between deformation parameters and time. This can be proved by the classic research done by predecessors and the model they proposed, such as Saito, Hayashi, Federico, and so on [18-20]. In subsequent studies, statistical methods, artificial neural network analysis methods, fuzzy mathematics methods, and many other advanced analysis methods have been applied to analyze and optimize the displacement and deformation parameters of slopes, and a large number of landslide prediction models have been proposed accroding to these methods[1,21]. Many of these models have been applied in practice, and some of them have successful cases in landslide early warning and prediction. However, almost all of the above models only involve the displacement and deformation parameters of the slope, and the important parameters about the mechanism of landslide have been neglected, which may lead to confusion about the causes of landslides and even lead to incorrect predictions. Although, some mechanical or strength parameters of slope, and other external factors causing landslides such as rainfall, engineering disturbance loads and seismic disturbance loads have been incorporated into many recent modified prediction models, sometimes it is very difficult to obtain these parameters accurately because of the common variability and nondeterminacy of these parameters[22-23]. If parameters are obtained incorrectly, the accuracy of landslide prediction will be greatly reduced. Thus, due to the complexity of landslide mechanism and process, it is still challenging to predict landslide accurately.

Therefore, in order to predict landslides more accurately and obtain relevant parameters easily, it is necessary to develop new prediction methods. This paper will give a new landslide prediction model from the view of considering the deformation parameters and sliding force that causes the landslide, based on the LURR theory.

Since the 1990s, LURR theory has seen wide applications and it was initially applied to the field of earthquake engineering, such as mine earthquake prediction, Yin et al. performed load-unload experiments of rock with a compression failure and regarded the stress as the response parameter [24-25]. Wan analyzed the applicability of LURR theory for different types of earthquake [26]. Zhang et al. introduced a damage variable based on LURR theory and damage mechanics [27]. Yuan et al. predicted future seismicity of Qiandao Lake region for the construction of submerged floating tunnel project by using LURR theory [28].

The LURR theory was firstly used for landslide prediction by Xu and Liang, they sought instability precursor and forecasted landslide with moderate scales [29]. The advantages over conventional methods were also illustrated in this study. He et al. forecasted landslides in Three Gorges Reservoir region by using the LURR theory [30-31]. Jiang et al. constructed a LURR model for a slope under seismic load and advocated to use the loading/unloading response degree (LURR) instead of the factor of safety [32]. Based on the LURR theory, Tang predicted the landslide acceleration in a typical reservoir landslide region [33]. Zhang et al. set rainfall and displacement as the parameters of LURR model and conducted a dynamic analysis of a earth-rock aggregate slope [34].

Although some problems still exist in the LURR method. One of the primary problems is the selection of the load-unload parameters. Previous studies primarily use rainfall parameter, ground water level, gravitational tides and so on [35]. In view of this, this study uses some mechanical parameters measured from remote intellectual monitoring as the load-unload parameters, and regards slope displacement measured by total station as the load-unload response parameters.

Since tidal forces induce periodical stress variation (can be viewed as continuous loading and unloading) inside the earth, Yin et al. considered tidal forces generated from the sun and moon movements as the load-unload factor [12,24]. Additionally, Xu and Liang study the unstable rock mass of Huangya near the left bank at Wujiangdu hydropower station using tidal forces as load-unload factors [29]. He et al. selected the groundwater variation and slope reservoir water level as the load-unload factors for colluvial landslide prediction [27]. He et al. also set monthly rainfall as the load-unload parameter to forecast colluvial landslides induced by rainfall [36]. So a LURR landslide prediction model, combining mechanics and deformation parameters, was established and applied in Antaibao and Pingzhuang west open-pit slopes.

The remainder of this study is organized as follows. In Section 3, the LURR landslide prediction model is established. In Section 4, the prediction model is verified by two open-pit slopes and the research results are discussed. Section 5 summarizes the conclusions.

3. METHODOLOGY

3.1. PRINCIPLE OF LURR THEORY

Based on the constitutive model of rock materials (as shown in Figure 1), the LURR describes mechanical behaviors of stressed rock materials in the whole load-unload phases. With the increase of stress, rock materials generally experience elastic deformation, damage, stability loss in sequence. The typical characteristic of elastic deformation is reversibility. In other words, both the processes of loading and unloading are reversible. Therefore, the loading response ratio equals to the unloading response ratio. However, the essential features of damage process are different from that of the elastic stage, as the loading response ratio is larger than the unloading response ratio, and the process is irreversible.

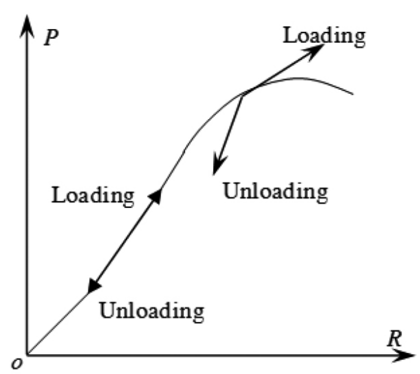


Fig. 1. Constitutive curve of rock materials

In LURR theory, suppose the load increment is ΔP, and the relevant response increment is ΔR. The response ratio can be defined by Equation 1.

$$X = \lim_{\Delta P \to 0} \frac{\Delta R}{\Delta P} \tag{1}$$

After periodic loading and unloading, assume X_+ and X_- represents response ratio for loading and unloading respectively. Then the LURR (Y) can be defined by Equation 2.

$$Y = \frac{X_+}{X_-} \tag{2}$$

For elastic deformation, the relation between loads (P) and response (R) is almost linear. Therefore, $X_+=X_-$ and Y=1. Different from the elastic deformation, loads are increasing and gradually approach critical value in damage process. Consequently, the system tends to be unstable, namely $X_+>X_-$ and Y>1. When the system is out of stability, $Y \longrightarrow \infty$.

From the aforementioned definition, it can be simply concluded that the LURR (Y) is effective to quantitatively depict the degree of tendency to instability for a nonlinear system. Geological disasters such as landslide, collapse, rock burst, earthquake and volcanic eruption are instabilities in different scales. Therefore, the LURR theory provides a new method for geological disaster prediction.

According to damage mechanics, the geological disaster development is similar to damage evolution of internal medium of geological bodies. In damage mechanics theory, damage processes are quantitatively interpreted by a damage variable D, which is defined by selecting an elasticity modulus M. The details are as follows.

It is very common to select a scalar elastic modulus to define the damage variable D. For example, Lemaitre gave the definition of D as shown in Equation 3.

$$D = \frac{E_0 - E}{E_0} = 1 - \frac{E}{E_0} \tag{3}$$

Where E_0 represents the initial modulus before damage, and E indicates the modulus under loading. Before damage, $E=E_0$ and D=0. When the material is completely destroyed, $E=0$ and D=1.

According to the definition of Y, a new formula can be derived as Equation 4.

$$Y = \frac{X_+}{X_-} = \frac{\Delta\varepsilon_+}{\Delta\sigma_+} \Big/ \frac{\Delta\varepsilon_-}{\Delta\sigma_-} = \frac{E_-}{E_+} \tag{4}$$

Since the modulus approximately equals to the initial one when the materials are under unloading, (namely $E_-=E_0$ and $E_+=E$), D can be expressed by Equation 5.

$$D = 1 - \frac{E}{E_0} = 1 - \frac{1}{Y} \tag{5}$$

It can be seen from the above equation: Y=1 will lead to D=0, which means the material is undamaged and stable. However, $Y \longrightarrow \infty$ results in D=1, which indicates the material has been completely damaged.

In most situations, when $D=D_c<1$, the material is stable. Therefore, D_c can be defined as critical damage value. Equations 3-5 can be converted to Equation 6.

$$Y_c = \frac{1}{1 - D_c} \tag{6}$$

Equations 5 and 6 reveal the relations between Y and D, which can be used to represent the geological disaster development.

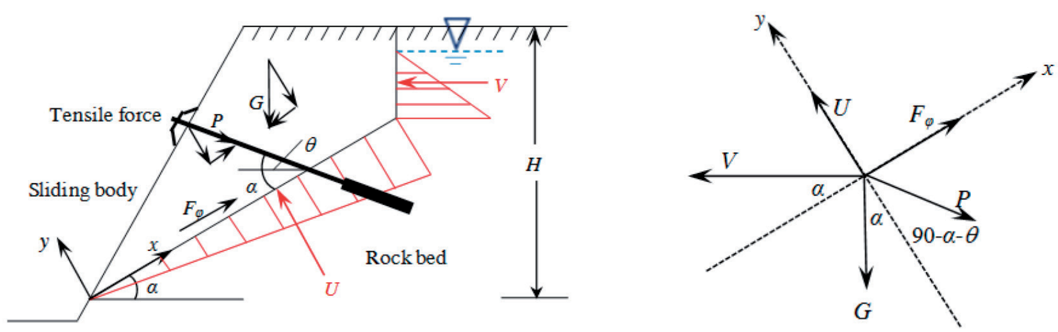
Many signs exist for the occurrence of a landslide. Similar to earthquakes, landslide development is very complicated, including a series of phenomena and processes, such as crack nucleation, sliding surface formation, consolidation, friction, cut-through, dislocation and so on. All these phenomena bring challenges to a clear understanding of the damage mechanics of landslide. Therefore, it is essential to determine the key issues of landslide prediction for this study.

3.2. PARAMETERS FOR LURR MODEL

3.2.1. Load-unload parameter

According to previous descriptions, selection of appropriate loading and unloading parameters is one of the key tasks. In this paper, sliding force was adopted to represent load-unload parameter. Sliding force is one of the forces involved in the natural mechanical system for a slope. The sliding force definitely indicates the loading and unloading inside the slope. However, how to obtain the sliding force remains a serious problem to be resolved. He proposed a new approach to monitor the sliding force variation [33]. In this method, a new mechanical equilibrium is built by introducing an external force to interact with the natural forces inside the slope. More specifically, insert a cable through the sliding surface to form a new mechanical equilibrium. The mechanics model and force diagram are plotted in Figure 2.

Natural forces inside a slope are very complicated. In order to simplify the problem, some assumptions are made as follows: (a) Sliding body as rigid without tensile and compressive deformations during sliding; (b) Sliding surface is a single plane; (c) Soil thrust on top of the slope and resistance force at the bottom are not considered; (d) Tak-



(a) Mechanics model (b) Force diagram

Fig. 2. Mechanics model and mechanics diagram

ing full account of lithological factors of *c* and ϕ, geometrical factors of *l*, α and θ, and underground water pressure of *U and V*.

Equation 7 demonstrates the mechanical equilibrium of the slope under the state of limit equilibrium.

$$G_t + V_t = P_t + F_\varphi \tag{7}$$

Where G_t is the tangential component of sliding body gravity, V_t is the tangential component of pore water pressure from trailing edge, P_t is the tangential component of tensile force from anchor, and F_ϕ is frictional forces along the sliding surface.

Sliding force is composed of G_t and V_t, which is the driving force for a landslide. Taking F_s to denote sliding force as follow.

$$F_s = P_t + F_\varphi \tag{8}$$

Based on Coulomb's law, Equation 9 can be derived as follow.

$$F_\varphi = (P_n + G_n - V_n - U)\cdot \tan\overline{\varphi} + c\cdot l \tag{9}$$

Where P_n is the normal component of tensile force in the anchor, G_n is the normal component of sliding body gravity, V_n is the normal component of pore water pressure from the back of the sliding mass, *U* is the pore water pressure perpendicular to sliding surface, $\overline{\varphi}$ is weighted average of internal friction angles for soil/rock layers, *c* is the cohesive and *l* is the length of sliding surface.

Combining the above equations yields, a new group of formula as follows.

$$F_s = k_1 P + k_2 \tag{10}$$

Where $k_1=\cos(\alpha+\theta)+\sin(\alpha+\theta)\cdot\tan\overline{\varphi}$, $k_2=G\cdot\cos\alpha\cdot\tan\overline{\varphi}-(U+V\cdot\sin\alpha)\cdot\tan\overline{\varphi}+c\cdot l$. And *α* represents the angle between sliding surface and horizontal plane, *θ* is the anchor's angle.

From the above description, it is obvious that the sliding force is related to many parameters inside the slopes, such as sliding body gravity, pore water pressure, properties of soils and rocks. Therefore, it is clear that sliding force can represent the loading and unloading processes inside the slopes. As shown in Equation 10, even though it is impossible to measure the original sliding force, one can obtain the sliding force variation by measuring the tensile force in an anchor.

In brief, sliding force is part of the mechanical system inside slope, it is scientific and rational to use it to demonstrate the load-unload behaviors. Moreover, the unmeasured sliding force variation can be effectively calculated by inserting an anchor into slope and measuring the tensile force.

3.2.2. Load-unload response parameter

After the determining of load-unload parameter, the corresponding response parameter selection is the next step. Previous studies showed that many kinds of mechanical and non-mechanical parameters can be used to denote the load-unload response, such as ground tilt, ground water level, borehole deviation, acoustic emission, ground deformation, and so on. Nevertheless, displacement monitoring is a frequently-used method for most slopes. Displacement data are always sufficient and hence are very convenient for usage. According to the existed studies, although displacement variation often appeared behind the sliding force, the corresponding relations between the two parameters were obvious, and the two parameters display similar trends [33]. According to the principle of LURR theory, all these characteristics show the rationality of selecting displacement as load-unload response parameter. Meanwhile, the related dynamic parameters, such as displacement velocity and displacement acceleration are introduced in following section.

3.3. LURR LANDSLIDE PREDICTION MODEL

According to previous description, sliding force variation was selected as the load-unload parameter, and displacement was taken as the response parameter. Meanwhile, some other related parameters derived from displacement, such as displacement velocity and displacement accelerated speed, were implemented in the LURR model. Consequently, several LURR landslide prediction models were constructed as follows.

3.3.1. Theoretical model based on sliding force and displacement

If sliding force and displacement are taken as the load-unload parameter and the response parameter respectively, the load-unload response ratio can be indicated by Equation 11.

$$Y_s = \frac{X_+}{X_-} = \frac{\Delta R^+}{\Delta P^+}\Big/\frac{\Delta R^-}{\Delta P^-} = \frac{\overline{\Delta D_s^+}}{\overline{\Delta F_s^+}}\Big/\frac{\overline{\Delta D_s^-}}{\overline{\Delta F_s^-}} \tag{11}$$

Where $\overline{\Delta F_s^+}$ and $\overline{\Delta F_s^-}$ re resent the mean value of sliding force variation in the state of loading and unloading respectively, which are given by Equations 12 to 13 as follows.

$$\overline{\Delta F_s^+} = \frac{1}{n}\sum_{i=1}^{n}(F_s - P_0) \tag{12}$$

$$\overline{\Delta F_s^-} = \frac{1}{n}\sum_{i=1}^{n}(P_0 - F_s) \tag{13}$$

Where P_0 represents the initial prestress value and F_s represent the sliding force.

Besides, for Equation 11, $\overline{\Delta D_s^+}$ and $\overline{\Delta D_s^-}$ represent the mean value of displacement variation in the state of loading and unloading respectively, depending on total changes of displacement in three directions D_s and initial value D_0.

$$D_s = \sqrt{D_x^2 + D_y^2 + D_z^2} \tag{14}$$

$$\Delta D_s^+ = D_s - D_0 \tag{15}$$

$$\Delta D_s^- = D_0 - D_s \tag{16}$$

$$\overline{\Delta D_s^+} = \frac{1}{n}\sum_{i=1}^{n}\Delta D_{si}^+ \tag{17}$$

$$\overline{\Delta D_s^-} = \frac{1}{n}\sum_{i=1}^{n}\Delta D_{si}^- \tag{18}$$

3.3.2. Theoretical model based on sliding force and displacement velocity

Similarly, if sliding force and displacement velocity are taken as the load-unload parameter and the response parameter respectively, the load-unload response ratio can be indicated by Equation 19.

$$Y_v = \frac{X_+}{X_-} = \frac{\Delta R^+}{\Delta P^+}\Big/\frac{\Delta R^-}{\Delta P^-} = \frac{\overline{\Delta D_v^+}}{\overline{\Delta F_s^+}}\Big/\frac{\overline{\Delta D_v^-}}{\overline{\Delta F_s^-}} \tag{19}$$

Where $\overline{\Delta D_v^+}$ and $\overline{\Delta D_v^-}$ represent the mean of displacement velocity variation in the state of loading and unloading respectively, and they can be expressed by Equations 20 and 21.

$$\overline{\Delta D_v^{\ +}} = \frac{1}{n}\sum_{i=1}^{n}\frac{\overline{\Delta D_{s(i+1)}} - \overline{\Delta D_{s(i)}}}{t} \tag{20}$$

$$\overline{\Delta D_v^{\ -}} = \frac{1}{n}\sum_{i=1}^{n}\frac{\overline{\Delta D_{s(i)}} - \overline{\Delta D_{s(i+1)}}}{t} \tag{21}$$

3.3.3. Theoretical model based on sliding force and displacement acceleration

In the same way as above, if sliding force and displacement acceleration are taken as the load-unload parameter and the response parameter respectively, the load-unload response ratio can be indicated by Equation 22.

$$Y_a = \frac{X_+}{X_-} = \frac{\Delta R^+}{\Delta P^+} \Big/ \frac{\Delta R^-}{\Delta P^-} = \frac{\overline{\Delta D_a^{\ +}}}{\Delta F_s^{\ +}} \Big/ \frac{\overline{\Delta D_a^{\ -}}}{\Delta F_s^{\ -}} \tag{22}$$

Where $\overline{\Delta D_a^+}$ and $\overline{\Delta D_a^-}$ represent the mean of displacement acceleration in the state of loading and unloading respectively, and they can be expressed by Equations 23 and 24.

$$\overline{\Delta D_a^{\ +}} = \frac{1}{n}\sum_{i=1}^{n}\frac{\overline{\Delta D_{v(i+1)}} - \overline{\Delta D_{v(i)}}}{t} \tag{23}$$

$$\overline{\Delta D_a^{\ -}} = \frac{1}{n}\sum_{i=1}^{n}\frac{\overline{\Delta D_{v(i)}} - \overline{\Delta D_{v(i+1)}}}{t} \tag{24}$$

4. ENGINEERING VERIFICATION ANALYSIS AND DISCUSSION

4.1. ANTAIBAO OPEN-PIT SLOPE ENGINEERING

The Antaibao open-pit is located in Shuozhou City, Shanxi Province, China. Its northern and western slopes were considered as research objects because they are adjacent to living and working areas, as shown in Figure 3. For the slopes, the width from

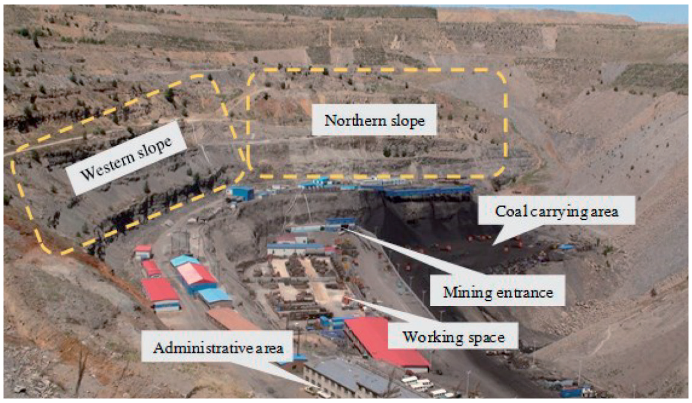


Fig. 3. Western and northern slopes in Antaibao open-pit

north to south at the pit bottom is approximately 130 m, and the length from east to west is about 270 m. At the early mining period, the western and northern slopes consist of several steps from top to bottom. The height of each step was 30 m and the width of each step was about 40 m. However, after the natural and man-made destruction, parts of the steps had been eroded, leading to much steeper slopes. The areas monitored and studied are mainly composed of loose soil, silty soil and silty clay. The bottom of the soil layer is high-strength rock, which does not have the risk of landslide, so it is not included in the monitoring.

As mentioned previously, it is vital to obtain the sliding force and displacement. In this case study, the sliding perturbion remote monitoring (SPRM) and georobot deformation monitoring system are used to measure the required parameters [37]. 30 monitoring points were designed for the western and northern slopes, and 30 sets of monitoring equipment were installed at the points locations. Compared with conventional deformation monitoring, the monitoring system adopted in this research involves more complicated installation process, including borehole drilling, anchor cable installation, grouting, reinforced concrete placement, instruments testing and installation, online monitoring system construction and so on. Construction processes of monitoring equipments and completed monitoring system can be summarized in Figure 4.

The diameter of the holes is 150 mm and the designed depths range from 45 to 60 m. The anchor cables for monitoring were composed of six pre-stressed steel strands with high strength and low relaxation. The diameter of each steel strand is 15.24 mm and, the strength grade is 1860 MPa. Each cable consists of two parts, the anchorage section and the free section. The anchorage section was protected from rusting and pollution, and the free section was painted with butter on the surface to prevent reinforcement corrosion. Meanwhile, the free section was covered with PVC tube to keep the anchor cable away from cement bonded sand. All cable forces can be transmitted online to re-

(a) Drilling construction

(b) Anchor installation

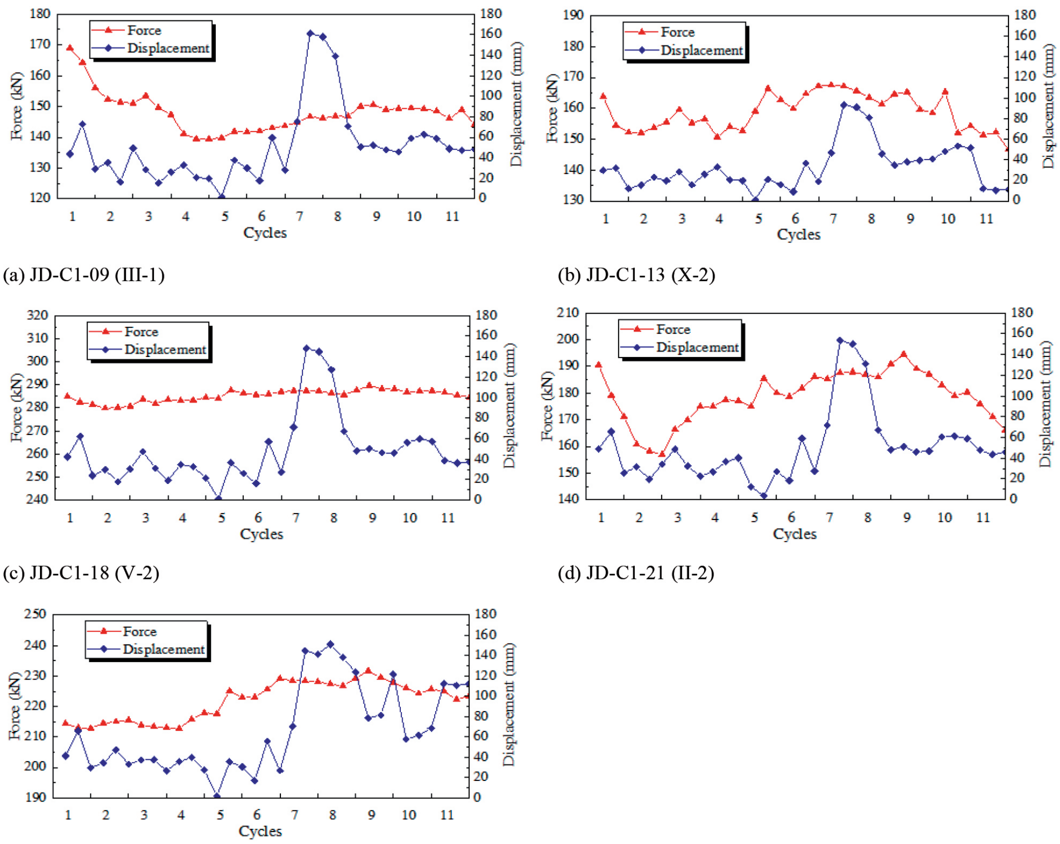
(c) Grouting in hole

(d) Stress Sensor

(e) Displacement measuring equipment

(f) Established monitoring system

Fig. 4. Construction processes and Established monitoring system



(a) JD-C1-09 (III-1)
(b) JD-C1-13 (X-2)
(c) JD-C1-18 (V-2)
(d) JD-C1-21 (II-2)
(e) JD-C1-24 (IV-3)

Fig. 5. LURR parameters for different measuring points

mote servers via stress sensors, and displacements can be obtained by the georobot. The two parameters in LURR model are numbered respectively. For example, the point number of load-unload parameter was named as III-1, while that of response parameter was named as JD-C1-09.

Through the aforementioned monitoring system, a large amount of monitoring data was obtained. The monitoring system received and transmitted data automatically. The data frequency was set as one set of data per 2 hours for each point. According to the key issues for LURR calculation, the raw data need to be processed before calculation to properly use the monitoring data. Several processing rules were set as follows: (a) Set the load-unload period as one month; (b) Calculate the average tensile force of early, middle and late months in each month, and take the mean again of the 3 tensile forces again in one month; (c) Compare the three tensile forces with the second set of mean values and calculate the difference between them. Take the maximum value as loading parameter. Similarly, the minimum value was considered as the unloading parameter.

To introduce the model proposed more simply, the data obtained within one year after the completion of the monitoring system are analyzed. Based on the above rules, some of the load-unload parameters and the response parameters are given as curves, as shown in Figure 5.

As an example, the computation process of LURR for monitoring point JD-C1-13 (X-2) was shown in Table I. In the table, loading and unloading stages are expressed by the signs of '+' and '-' respectively. Based on these information, Equation 11 is used to calculate the value of LURR, as shown in the last column in Table I. Finally, the LURR curve can be generated using the information in Table I as shown in Figure 6. From the LURR curve in Figure 6(See section: supplementary material), it can be concluded that the LURR is mainly around 1.0, indicating that the slope area around this point is stable.

For further analyses, the slopes was divided into five areas, as shown in Figure 7. The topography of the slope varies significantly across the studies area. In areas I and II, located in the north, the slope is very steep. The underground mining and coal transporting road entrances are under these two areas. Therefore, it is vital to control the stability of these two areas. Area III is located in the corner of the whole slope and between areas II and IV. Area V is near the west edge of the study slope. Several landslide disasters once occurred in area V. Therefore, more attention needs to be paid to this area. The LURR of these five areas were plotted in Figure 8(See section: supplementary material). Moreover, LURR frequencies were shown in Figures 9 and 10(See section: supplementary material).

By analyzing the LURR results Y of the five areas, the following phenomena are observed.

(a) LURR time-sequence curves of the five areas generally fluctuate around the value of 1.0, without obvious up and down trends, indicating that the slope is stable.

(b) Compared to the other four areas, the LURR curve of area V exhibits larger variation and the frequency of $Y \geq 1.5$ is higher, as shown in Figure 9 (See section: supplementary material). Actually, it was found by geological surveying that landslide disasters occurred several times in area V. These descriptions show that the slope in area V is not as stable as those in other areas. Although many safety control measures have been taken in this area, continuously monitoring works should be implemented. On the contrary, the LURR frequency of $Y \geq 1.5$ in area IV is the lowest, also indicating the stable conditions in this area.

(c) Comparing the several time-sequence curves, including loading/unloading parameter, loading/unloading response parameter and LURR ones, it can be concluded that the stability and trends among them increase gradually, LURR results have the most regular curves. Therefore, the application of tensile force and displacement based on LURR theory improves the efficiency and accuracy of landslide prediction.

4.2. PINGZHUANG WEST OPEN-PIT SLOPE ENGINEERING

Pingzhuang west open-pit slope located in Chifeng City, China, as shown in Figure 11. The east side of the mine is a non-working slope and the west side is a working slope. The rock mass of the slope is unstable and landslide disasters often occur. According to records, there were 66 landslides occurrence in this open-pit mine. The upper part of the slope in the study area is mainly composed of loose soil, while the lower part is mainly composed of mudstone and sandstone with developed joints and fractures, which leads to poor stability of the slope, especially those joints and fractures developing along the slope.

Fig. 7. Division of research areas in Antaibao open-pit slope

In view of the present situation of the slope, a sliding force-displacement monitoring system with 17 Measuring points is established here, which has successfully predicted several large landslides. For simplicity, only one of the forecasts is illustrated for an example. It should be explained that the landslide was very dangerous. Fortunately, a large number of sliding force and displacement data were obtained by the monitoring system. Thus, the occurrence time of the landslide disaster had been predicted in advance, which has successfully avoided casualties and equipment damage.

Considering that the monitoring data change greatly in a short time, the loading and unloading cycle can be shortened to 10 days according to the above idea. The calculated sliding force, displacement and LURR are shown in Figure 12(See section: supplementary material). About 40 days before the landslide, the detected sliding force and displacement was gradually increasing, and the LURR was rising with a value greater than 1, which indicated that the stability of the slope is gradually deteriorating. In the second loading and unloading cycle before landslide, the LURR increases sharply, and the value is greater than 1.5, which implies that the slope was already in a very dangerous state. After a few days, with the increase of slope displacement, some monitoring equipment stopped working because of cable damage. Four days later, the landslide happened. As the landslide was known in advance, the personnel and equipment near the slope were evacuated in time, so no casualties or equipment damage was caused.

Before the landslide, the evolution process of cracks on the top surface of the slope is shown in Figure 13(See section: supplementary material). 70 days before the landslide, there were no abnormal phenomena on the surface that could be observed with the naked eye. Until 40 days before the landslide, some small cracks appeared. Moreover, the width of the crack is gradually increasing. When the landslide is about to occur, the maximum crack width reaches 500 mm.

By comparing the LURR curve with the observed phenomena in the field, it is obvious that the landslide prediction based on the load-unload response ratio theory is very accurate. All the above evidences and phenomena verify the correctness of the model proposed in this study.

Cycle number	Average value	Tensile force difference ΔF_s (kN)	Displacement difference ΔD_s (mm)	Loading/ unloading interval	LURR Y_s
1	$\overline{F_s}$ =163.13	5.89	24.05	+	1.50
	$\overline{D_s}$ =48.69	1.18	-4.80		
		-7.08	-19.26	-	
2	$\overline{F_s}$ =151.60	0.71	15.49	+	0.68
	$\overline{D_s}$ =33.84	-0.17	1.71		
		-0.53	-17.20	-	
3	$\overline{F_s}$ =150.16	3.32	5.11	+	0.55
	$\overline{D_s}$ =23.36	-0.54	2.65		
		-2.77	-7.76	-	
4	$\overline{F_s}$ =140.05	1.10	8.31	+	0.96
	$\overline{D_s}$ =24.51	-0.51	-3.71		
		-0.58	-4.61	-	
5	$\overline{F_s}$ =141.17	0.74	14.51	+	1.20
	$\overline{D_s}$ =23.15	0.56	6.82		
		-1.30	-21.33	-	
6	$\overline{F_s}$ =142.90	0.76	24.40	+	1.62
	$\overline{D_s}$ =35.20	0.12	-6.94		
		-0.88	-17.46	-	
7	$\overline{F_s}$ =145.95	0.77	29.79	+	0.71
	$\overline{D_s}$ =131.52	0.27	26.37		
		-1.03	-56.16	-	
8	$\overline{F_s}$ =147.91	2.19	52.21	+	0.75
	$\overline{D_s}$ =86.80	-1.05	-15.94		
		-1.15	-36.28	-	
9	$\overline{F_s}$ =149.64	0.96	3.72	+	0.88
	$\overline{D_s}$ =48.62	-0.29	-0.78		
		-0.66	-2.94	-	
10	$\overline{F_s}$ =149.07	0.41	2.57	+	2.59
	$\overline{D_s}$ =60.27	0.12	-1.28		
		-0.54	-1.29	-	
11	$\overline{F_s}$ =146.40	2.54	0.80	+	1.14
	$\overline{D_s}$ =48.06	-0.33	0.00		
		-2.22	-0.81	-	

Table I LURR parameters analysis for monitoring point JD-C1-13 (X-2)

4.3. DISCUSSION

For landslide disaster prediction and early-warning, the mathematical mechanics evaluation method and displacement time sequence analysis method have been


Fig. 11. Pingzhuang west open-pit slope

playing important roles in recent years. It is essential to introduce physical mechanical parameters such as cohesion, internal friction angle, elasticity modulus, Poisson ratio and geometry boundary conditions to mathematical mechanics evaluation method. However, it was very difficult to measure the physical mechanical parameters and prediction results based on this method, hence, has a low accuracy. In certain degree, displacement time sequence analysis method has overcome the aforementioned disadvantages. However, this method primarily considers the influence factors of displacement velocity and acceleration rate and seldom involves landslide physical processes. This characteristic of the method leads to inefficient landslide prediction, regardless of loading/unloading dynamics process. For the aforementioned reasons, LURR theory was introduced in this study for landslide prediction. In this paper, mechanical and displacement parameters were considered and integrated for prediction model establishment. Consequently, the shortcomings of mathematical mechanics evaluation method and displacement time sequence analysis method were minimized. With the implementation of LURR theory, a new approach for landslide prediction was developed.

It is impractical to build a model involving all the related theoretical parameters for landslide prediction. In order to conduct the prediction efficiently, some simplifications were made in this study. Therefore, to some extent, this model may be able to be further improved.

Curves of different parameters show that the curves vary significantly for either load-unload parameter or load-unload response parameter. However, the trend of LURR curves was relatively stable. Therefore, it is much easier to summarize the disciplines, and more effective to implement landslide prediction and early-warning by LURR results.

Comparing with the variation amplitude of tensile force and displacement, the dynamic trends of the time sequence curves indicate that it is more reasonable to select the tensile force as the load-unload parameter than displacement, because the variation of tensile force curves is periodical, insusceptible and regular.

5. CONCLUSIONS

To predict landslide disasters accurately, a landslide prediction model based on LURR was proposed and it was verified in two open-pit slope engineering, the following conclusions can be drawn.

(1) From the expressions of loading response ratio and unloading response ratio, it can be seen that the LURR theory is very suitable for evaluating the non-linear loading and unloading process, which has been successfully applied in non-linear damage assessment in geotechnical engineering. Rocks and soils that constitute slopes are typical non-linear materials, and the failure of the slope also has corresponding non-linear mechanical characteristics. Therefore, it is appropriate to apply the LURR theory to landslide displacement evaluation and prediction.

(2) The process of landslide is accompanied by very complex physical and mechanical changes, such as the strength reduction of rocks or soils, the increase of landslide sliding force, the slope displacement and deformation, and so on. In fact, the direct cause of landslide is that the anti-sliding force is less than the sliding force, while what we can see from the naked eye is the displacement and deformation of the slope that caused by these unbalanced forces. Thus, it is more accurate and faster to judge whether the slope is unstable by analyzing the displacement/deformation of the slope and the change of the sliding force, compared with those methods that only use displacement parameters. In addition, the displacement/deformation parameters and the sliding force parameters can be obtained easily and accurately, while those parameters with strong variability and uncertainty are avoided. Therefore, it is scientific and reasonable to choose the displacement and the anchor cable force as the parameters of the landslide prediction model that based on the LURR theory.

(3) The new landslide prediction model based on the LURR theory involving the tensile force and the displacement parameters. It can be combined with modern technologies such as intelligent sensing, remote transmission, and Internet technology to realize remote online real-time monitoring of landslides. Besides, by replacing the displacement parameters with displacement velocity or displacement acceleration, new similar models can be obtained, which can cooperate with the old model to verify the possibility of landslide.

(4) The proposed landslide prediction model has been applied to Antaibao open-pit slopes and Pingzhuang west open-pit slopes. The successful forecasting experience shows that the curve of LURR presents obvious and intuitive changes when the slope is about to slide. By comparing the cracks and subsidence observed at the top of the slope before the landslide occurs, it can be proved that the model predicted the landslide accurately and effectively prevents the loss of life and property.

A landslide prediction model based on LURR theory was proposed and it was verified in two open-pit slopes in this study. As different materials respond differently to loading and unloading processes, slopes composed of different materials may have different loading and unloading responses. Thus, in the further research work, it is necessary to carry out field tests on different slopes that constituted different materials, and find out the inherent laws that may exist in order to accurately predict and forecast various types of landslides. However, it can be ascertained that the model is applicable as long as the material has non-linear mechanical characteristics. In addition, with the development of the monitoring and information technology, the intelligent prediction method for slope engineering involving multiple sliding surface and considering time and location early warning needs to be further researched.

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SUPPLEMENTARY MATERIAL

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