A new method for time prediction of slope failure

Une nouvelle méthode pour prédire le moment de l'écroulement d'un talus

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ABSTRACT: A new method for time prediction of slope failure was proposed based on the plastic deformation power and creep rupture in company with the basic principle of slope failure in this paper,which was presented for the three key problems on time prediction of slope failure,such as,the phases of slope deformation,the whole state of slope deformation,and the time of slope failure.The method had been successfully used to predict the failure time for three slopes in advance.

RESUME: Ce texte présente brièvement une nouvelle méthode pour prévoir le temps de la destruction de pente.Cette méthode est proposée sur la base des caractéristiques de destruction à cause des déformations plastiques et vermiculaires de roche et sol,combinant avec la nature et la règle du glissement de terrain causé par la destruction de pente.Cette nouvelle méthode a résolu principalement trois problèmes cruciaux techniques concernant l'étape,l'intégralite et le temps sur la déformation de pente,et on a réussi à utiliser cette methode dans la pratique à prévoir successivement le temps des destructions de trois pentes.

1 INTRODUCTION

Generally,a great deal of life and property loss was caused by landslide disasters triggered from slopes,the time prediction of slope failure is one of the main problems during the research on landslides.Since Saito(1965),a Japanese scholar,proposed a method for predicting the failure time of a slope based on the creep rupture of slope,many experts and scholars all over the world have researched on the theory and method of failure time prediction for slopes theoretically,experimently and practically.Their theories and methods have obtained some achivements by applying in the practice of failure time prediction for slopes,but there is not a reasonable and feasible method for that yet.The present authors proposed a new method for time prediction of slope failure based on the plastic deformation power and creep rupture in company with the basic principle of slope failure,this method was used successfully in the failure time prediction of a large slope in 1995,and other two slopes were predicted exactly in 1996.A new method of monitoring and predicting for slopes was presented,which have been examined and improved one by one in practice.

2 BASIC THEORY

The basic theory of the failure time prediction for slopes is the 'Deformation Power' theory of slope body.That is,during the active deformation of a slope,dividing the deformation phases based on the deformation power of the slope,once the deformation is justified into the short term prediction phase or the phase just before the abrupt sliding of the slope,the failure time can be predicted by selecting the deformation energy of slope as the parameter for the failure time prediction.

2.1 Basic points

It is well known that a slope would fail into a landslide when the slope body absorbs the plastic deformation energy up to a critical value,the slope failure called.The plastic deformation energy is a monotonously increasing value on time while a slope is developing into a landslide,which can be adopted as the scale of internal time of slope developing.So it is possible to select the plastic deformation energy as the parameter of time prediction for slope failure.Otherwise,by analysing the plastic deformation power which represents the plastic deformation ability of a slope,this value is not always monotonously increasing on time,and it can not be selected as the scale of time prediction for slope failure.However,there is a critical plastic deformation power based on the limit analysis of Plastic Mechanics in company with the plastic deformation of slope failure,failure power called.The developing phases of slope failure can be distinguished and determined by comparing the relative value between the deformation power and the failure power of a slope,that is,a standard can be worked out to justify the deformation phases for slopes.The new method of failure time prediction for slopes based on the plastic deformation power as the judging standard to divide the deformation phases of a slope, and to select the deformation energy as the time prediction paramater to determine the failure time of slope once the slope deformation is justified into the short term prediction phase or the prediction phase just before the abrupt sliding.

2.2 Basic assumptions

A typical slope is shown in Figure 1,some basic assumptions are founded for the new method as following:

1.The plastic deformation zone of a slope comes togather along the sliding line or sliding surface,that is,gathering in a thin layer near the slip zone.This assumption corresponds with a lot of facts of slope failure.

2.The pratical failure slip surface of a slope S_D is known,which can be determined in advance by prospecting, monitoring and theoretical calculating.And it is supposed that the thin plastic deformation zone comes out along S_D stage by stage while a slope is developing into a landslide,and runs throughout as S_D at the failure time,this plastic deformation zone is signed as S_D^t. $S_D^t = S_D$ in location,but S_D^t runs throughout only when the slope fails into a landslide.

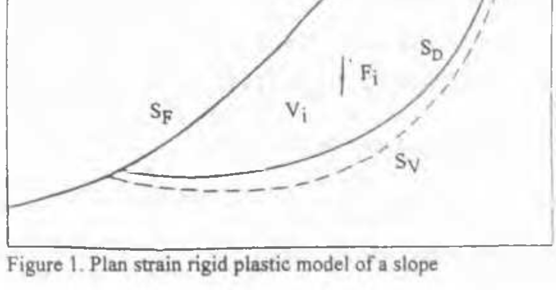

Figure 1. Plan strain rigid plastic model of a slope

3.The proceeding of slope developing into a landslide corresponds with the general creep principle of the deformation failure of soil and rock,and the proceeding is a quasi-static,the energy worked by the external force (Weight) at any time is used up in the plastic deformation of slope.

2.3 Basic formula

2.3.1 Calculating the deformation power and deformation energy

Combining assumption 1 with assumption 2 presented above,at any time while a slope is developing into a landslide,we have:

Plastic deformation power= $\int_{S_D^t} k[V_t^t]dS_D^t$ (1)

Plastic deformation energy= $\int_0^t \int_{S_D^t} k[V_t^t]dS_D^t dt$ (2)

By using the invented energy principle and the law of conservation of energy based on assumption 3 ,and calculating with the slices method,we have:

$$\int_{S_D^t} k[V_t^t]dS_D^t = \int_v F_i V_i^t dv \quad (3)$$

$$\int_0^t \int_{S_D^t} k[V_t^t]dS_D^t = \int_v F_i S_i^t dv \quad (4)$$

So the plastic deformation power and plastic deformation energy can be calculated from the power and energy worked by the external force (Weight) at any time,where,V_i^t and S_i^t can be obtained from the field monitoring.

2.3.2 Applying with the lower bound theorem in the limit analysis

Based on the lower bound theorem in the limit analysis of slope,the external force (Weight) corresponding with any stress field of equilibrium is the lower bound of the real failure load,we have:

$$\int_v F_i^p V_i^p > \int_v F_i V_i^p dv \quad (5)$$

where,"p" means the real value when a slope fails,and F_i^t is called the weight value at any time.

Once a slope is developing into the third creeping stage,the accelerating creeping state called,the deformation velocity is monotonously increasing,that is,if $t_2>t_1$ (t_1, t_2 is the time the developing of slope lasts),we have:

$$V_i^t(t_1) < V_i^t(t_2) < V_i^p \quad (6)$$

$$\int_v F_i^t V_i^p dv > \int_v F_i^t V_i^t dv \quad (7)$$

The above equations come togather,we have:

$$\int_v F_i^p V_i^p dv > \int_v F_i^t V_i^t dv \quad (8)$$

The equation shows that the plastic deformation power is monotonously increasing during the third creeping stage of a slope,and up to the critical value when the slope fails into a landslide,the failure power called.

2.3.3 Calculating the failure power

Based on the invented energy principle,we have:

$$\int_v F_i^p V_i^p dv > \int_{S_D} k[V_t^p]dS_D \quad (9)$$

where,$[V_t P]$ can be calculated from the flow rule.

$$[V_t^p] = \frac{\lambda}{2}\int_0^h [\sqrt{\frac{(\sigma_y-\sigma_x)^2}{\sigma_y\sigma_x+\tau_{xy}^2}} - f_o]\sin\alpha\, dy \quad (10)$$

then,the failure power can be worked out from the above two equations.

The dynamic proceeding,while a slope fails and is triggerred into a landslide,is the plastic developing of the slip zone of the landslide,that is,the soil and rock along the slip zone fails regressively,and the slip zone runs through completely,the landslide occurres as a result.According to the plastic theory appiled in the plan strain problem of rigid plastic body,the deformation power of a slope at any time is no more than at the failure state,the failure power called,and the failure power of a slope is a certain value which can be calculated by using some mathematic analysis methods.Meantime,the deformation energy must sastify the criterion of regressive rupture based on the character of deformation failure of a slope,and reach a peak to enable the slope fall down with a whole body.Therefore,the deformation power can be used as the standard to divide the deformation phases for a slope,and the deformation energy can be used to predict the failure time of the slope.

The theory and method above is able to consider the basic factors of a slope comprehensively,such as,the slope deformation,the velocity of displacemet,the volume of slope body,the shape and shear strength of slip zone,as well as,to show the active principle of the deformation of a slope.

3 MAIN SKILLS

The failure time prediction for a slope is usually divided into four phases,such as,the long term prediction,the middle term prediction,the short term prediction and the prediction just before sliding.However,a lot of research and practice have shown that the long and middle term prediction presented the distinct indefinition because of the random and complex during the active deformation of a slope,which should belong to the research on the stability analysis and evalution for slopes;that the active deformation of the slope changed from indefinition to definition during the short term prediction,the failure time prediction for slopes would show itself real meaning and the probablity to carry out at this time.The aim to propose the new method for the failure time prediction is to strengthen the research on the short term prediction,and emphasisly to solve the prediction just before sliding for slopes.

The predicting strategy used in the failure time prediction for slope is to adopt various measures,monitor systematically,analyse with individual points,predict with all of the points,decide comprehensively,and minimize landslide disasters from slope failure.The main skills are shown as following:

1.Arrang the geological survey reasonably to master the geological background and the environmental conditions for a slope.

2.Monitor systematically with various measures to obtain the real and feasible data of the slope deformation,abstract the valid information to the law of active deformation for a slope.

3.Caculate the deformation power and the failure power of a slope,check the relative level between them.Meantime,consider the macro traces of slope deformation to justify the deformation phases for a slope comprehensively.And both the deformation phase for short term prediction and the deformation phase for prediction just before sliding can be divided and determined reasonably.

4.During the monitoring for the deformation of a slope,either the monitoring network or the monitoring line is consist of monitoring points,which are able to react and feel the deformation and active principle for local masses of a slope respectively.Therefore,it is necessary to analyse individual points by using the regressing method based on their own deformation information.

5.Because of the local active traits in the individual points,the results from analsing individual points must be divergent,which is not able to represent and react the deformation state of the whole slope.So the predicting technology with all points based on the deformation energy presented above has to be adopted to calculate and determine the failure time of the whole slope.

6.According to the results from both analysing with individual points and predicting with all points,considering the macro traces of slope deformation and other relative factors as well,justify scientifically and warn comprehensively to adopt valid measures in time for precasting and minimizing the slide disaster.

4 EXAMPLES

Based on the new method for time prediction of slope failure presented above,three landslides were forecasted successfully in about a year,and the predicting technique was improved step by step.

4.1 Huangci Landslide

Huangci Landslide was located in Yingjing County,Gansu Province of China.The slide mass was 370 m long,300 m wide on toe,500 m wide on head,40 m thick on the average and 6 million m^3 in volume.There were about 40 m thick loess in the upper of landslide,interlayers with sandstone and mudstone underlying,and 5 to 8 m thick cobble layer interbeded.

The landslide is a typical old landslide.More than ten years ago,many extensive cracks were found on the head of the landslide.In recent years,both the lateral sides were developing and formating regressively.Especially,the shearing cracks on the toe were found and jointed togather completely in the late half year of 1994,and the deformation of the landslide developed more actively day by day,which was shown as the state in accelerating creeping.The major triggering reason was the effect of irrigation by bumping water from Yellow River.Because of the seepage of irrigation,the soil or rock near the slip zone was softened,and the shear strength of the slip zone was descended down,finally,Huangci Landslide occurred.To monitor the active state of the deformation for Huangci Landslide,a lot of monitoring measures were installed on the slip body or the boundary,such as,the displacement network,automatic extention meters,simple extension meters,tilt meters,inclination meters and acoustic emission meters.These apparatus were able to control and master the active state of the landslide deformation,which provided a base for predicting the failure time of Huangci Landslide exactly.The results of prediction for Huangci Landslide was shown in Table 1.

Table 1.Results of time prediction for Huangci Landslide

calculating time	predicted time	prior (days)	error (days)
Dec.22,1994	Jan.27,1995	39	-3
Dec.29,1994	Jan.23,1995	32	-7
Jan. 6,1995	Jan.26,1995	24	-4
Jan. 25,1995	Jan.31,1995	5	+1

In practice,Huangci Landslide slided down abruptly with whole body on 30 January 1995,there was only one day between the predicted time and the practical failure time of the landslide.Although the landslide disaster was very serious with large scale and sudden failure,more than 2000 residents and price objects had been moved out of the dangerous circle of landslide in advance,nobody was killed or wounded in the catastrophe,and the loss of property was declined down to the minimum level.

4.2 Tanhuaguichang Landslide

Tanhuaguichang Landslide with steep slope,3 kilometers far from Huangci Landslide,was standed behind a small chemical factory.The stability of slope was depressed day by day since October 1995,a monitoring system for the active state of slope deformation was founded to prevent the probable loss of landslide disaster,and the calculation and analysis of failure time for Tanhuaguichang Landslide was carried out.The predicted results in Table 2 had shown that Tanhuaguichang Landslide would fail on 6 Feberary 1996.In result,the landslide with 30,000 m^3 in volume falled down rapidly at 3:51 in that morning,the predicted time was very exact,nobody killed or wounded,and nothing lost.

4.3 Jiaoja Landslide

Jiaoja Landslide was located in Jiaoja Village,Yingjing County,Gansu Province of China,next to Tanhuaguichang Landslide.The landslide was 190 m wide,120 m long,40 to 50 m thick and 400,000 m^3 in volume.The top of landslide was a loess plateau with 40 m thick,the toe of landslide was 5 to 10 m thick accumulator overlaid on the cobble layer.The landslide had ever slided down in 1992,which incurred a catastrophe.Many cracks were found on the slope body since the early half year of 1995,the major reborn reason was the large scale irrigation for farming on the loess plateau,this landslide was a typical one along the brink of loess plateau,which generally incurred abrupt,rapid,extensive and large scale landslide disaster,so the systematic monitoring and predicting was worked out for that.The results for predicting the failure time of Jiaoja Landslide was shown in Table 3.

Table 2.Results of time prediction for Tanhuaguichang Landslide

calculating time	predicted time	prior (days)	error (days)
Jan.26,1996	Feb.2,1996	7	-4
Feb. 2,1996	Feb.4,1996	4	-2
Feb. 4,1996	Feb.6,1996	1	0

Table 3.Results of time prediction for Jiaoja Landslide

calculating time	predicted time	prior (days)	error (days)
Jan. 6,1996	Feb.12,1996	38	-1
Jan. 16,1996	Feb.19,1996	28	+6
Feb.12,1996	Feb.13,1996	1	0

Table 4.Results of hour prediction for Jiaoja Landslide

calculating time	predicted time	prior (hours)	error (minutes)
21:00,Feb.12	00:29,Feb.13	4	39
00:00,Feb.13	01:00,Feb.13	1	8

In order to increase the precision of failure time prediction,the hour prediction as a new concept was put forward,and shown in Table 4.

In result,Jiaoja Landslide slided down with a whole body abruptly and rapidly at 1:08 on 13 Feberary 1996,the toe of the landslide moved forward about 300 m away,the prediction of failure time was very exact,the error of hour prediction was only 8 minutes,and the loss of landslide disaster was minimal.

5 CONCLUSION

In the prediction of failure time for slopes,a new theory and method based on the deformation power and deformation energy of slope body was proposed.The successful practices had shown that the theory and method for predicting failure time of a slope got some notable improvements.Firstly,the division of deformation phases of a slope was solved reasonably,it was able to determine the short term prediction and the prediction just before abrupt sliding feasibly to improve the validity of prediction for slopes;Secondly,a single predicting parameter could be selected and determined to represent the whole landslide,which would play a very important role in the failure time prediction for large scale slopes;Thirdly,the method could overcome the undulation in the deformation of local masses in a slope body;Fourthly,a simple and practical method to determine the failure time exactly was worked out.In a word,the typical character of this new method for predicting the failure time of slope presented the feasiblity in theory,the validity in practice and the precision in result.

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