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Research on evaluation model of catastrophe progression for slope instability based on GIS and its application

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ABSTRACT

The catastrophe progression method is a multiple criteria evaluation based on the catastrophe theory and fuzzy mathematics. In this paper, a new computer program on based on GIS was developed by using VB.NET, with example of the engineering project of Xiaolongtan, Yunnan Province. The evaluation of catastrophe progression of slope safety in Xiaolongtan was carried out using 17 evaluation indexes of this program. The evaluation result is more reasonable and provides the reliable basis for the evaluation of slope instability.

KEYWORDS

GIS; Catastrophe progression; Slope instability; Evaluation model.

INTRODUCTION

In the activities of nature and human, there are a lot of sudden and transition change phenomena in addition to the continuous and gradual change phenomena. Slope instability problem is one of them. How to solve this problem, many authors proposed a new practical evaluation method (mutation progression method) based on the catastrophe theory.

METHODS

Evaluation methods of landslide disaster

The catastrophe evaluation is increasingly becoming a mean to reduce the landslide disaster. There are mathematic prediction model, information value method, fuzzy identification, pattern discrimination,gray model, fractal theory, mechanical calculation model of slope stabilization at present. The catastrophe progression method is a multiple criteria evaluation based on the catastrophe theory and fuzzy mathematics.

The catastrophe progression combined the fuzzy mathematics with mutations in mathematics, and calculated the contradiction relation with the unitary formula. Its essence is a kind of multidimensional fuzzy subordinate function based on abstract, complex and multi-objective fuzzy subordinate function[1,2].

Evaluation method of catastrophe progression

The main steps of catastrophe progression method are: factorizing the judging goal of system according to the multi-level, calculating dimension-less values by using range-method, and then carrying out the comprehensive quantitative calculating of state parameter by using the unitary formula. That means that the total subordinate function and the final evaluation result is obtained. The catastrophe progression method is a combination of quantitative and qualitative ones, which weighed the relative importance of each evaluation index without using the index weight. This method reduced the subjectivity of general fuzzy algorithm without sacrificing the science and reasonableness, so that is accurate and easy to apply to many fields.

Basic idea

Seven catastrophe models were put forward by Thomm, of which cusp catastrophe model, coattail catastrophe model and butterfly mutation model are commonly used. The specific functions of these three models are as follows: [3]:

(1) Cusp catastrophe model $V(x) = \frac{x^4}{4} + \frac{ax^2}{2} + bx$

(2) Coattail catastrophe model $V(x) = \frac{x^5}{5} + \frac{ax^3}{3} + \frac{bx^2}{2} + cx$

(3) Butterfly mutation model $V(x) = \frac{x^6}{6} + \frac{ax^4}{4} + \frac{bx^3}{3} + \frac{cx^2}{2} + dx$

Of which V(X) is potential function of a state variable x, and a, b, c, d are state variable system, representing the control variables of this state variable.

The evaluation index is undimensionalized by using range analysis method to eliminate the incommensurability due to different dimensions and dimensional units. The undimensionalized formulae are as follows[4]:

(1) Type of bigger is better $y_{ij} = \frac{x_{ij} - x_{\min(j)}}{x_{\max(j)} - x_{\min(j)}}$

(2) Type of smaller is better $y_{ij} = \frac{x_{\max(j)} - x_{ij}}{x_{\max(j)} - x_{\min(j)}}$

Of which x_{ij} is original data, $x_{\min(j)}$ is the minimum among the row j, $x_{\max(j)}$ is the maximum among the row j, y_{ij} is the data obtained by using range-method[4]. When the values of the control variables are [0,1], the data can be calculate by mutation progression without processing.

After deduction of above three models, the unitary formula is obtained. Set x as state variables, c1, c2, c3, c4 as control variables, the unitary formulae are shown as following:

(1) Unitary formula of cusp catastrophic $x_1 = c_1^{1/2}$, $x_2 = c_2^{1/3}$

(2) Unitary formula of coattail catastrophe $x_1 = c_1^{1/2}$, $x_2 = c_2^{1/3}$, $x_3 = c_3^{1/4}$

(3) Unitary formula of butterfly mutation $x_1 = c_1^{1/2}$, $x_2 = c_2^{1/3}$, $x_3 = c_3^{1/4}$, $x_4 = c_4^{1/5}$

Programming

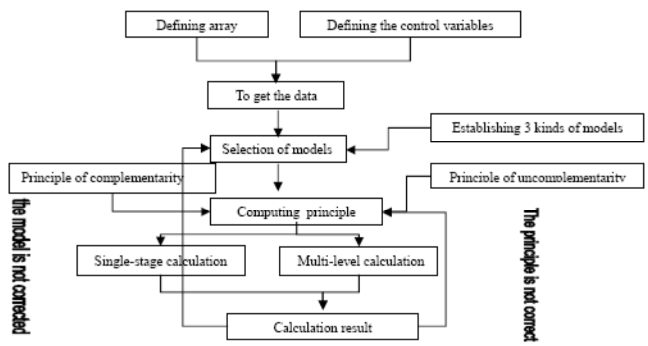

Figure 1 : Calculation flow chart on catastrophe progression model

The article focused on the forecasting technology of slope instability and developed the forecasting system of slope instability based on GIS By adopting the Super Objects secondary development method in SUPERMAP and programming language of VB.NET. This system can realize the computer solution on slope unstability and the visualization of evaluate result. The process is shown in Figure 1.

According to the monitoring data fromYunnan Xiaolongtan mine and the actual survey data from engineering geological investigation, the program of catastrophe progression model of the data and the evaluation model of catastrophe progression of the slope are developed.

(1)Monitoring model

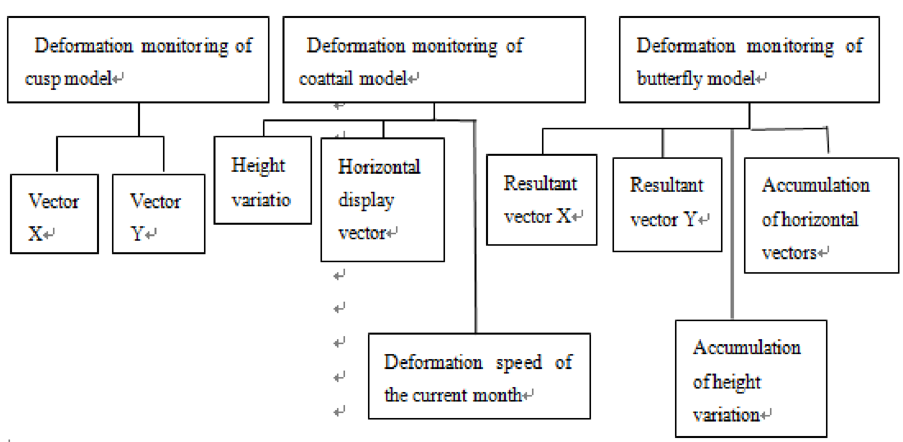

Figure 2 : System of single-stage indicators

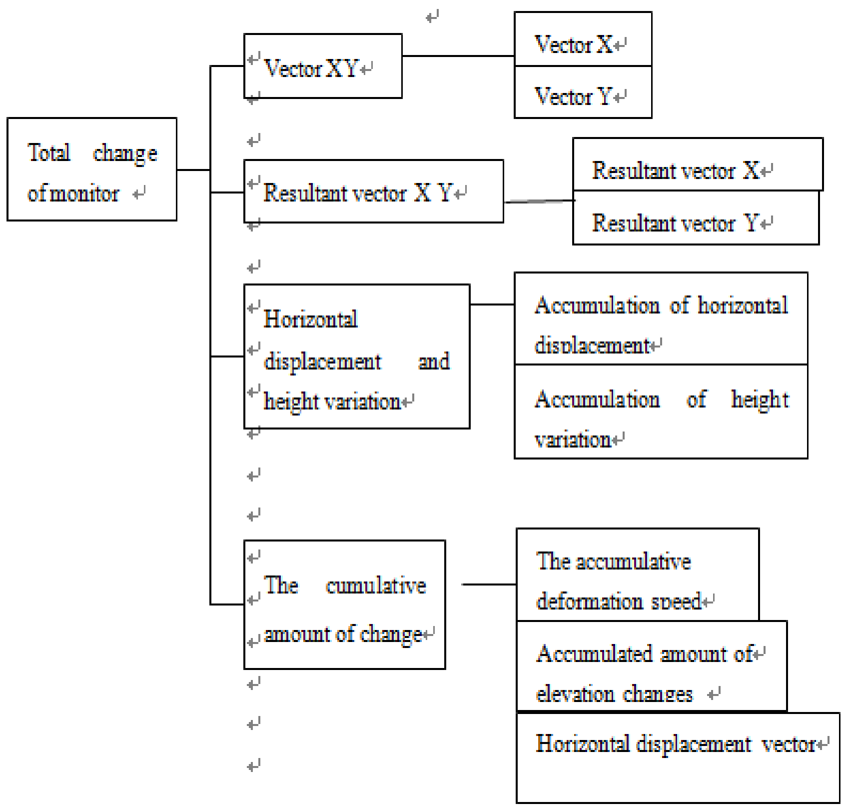

Figure 3 : System of multi-step

The ten values of the vector X, vector Y, height variation, horizontal displacement vector, deformation speed of the current month, resultant vector X, resultant vector Y, accumulation of height variation, accumulation of horizontal displacement, accumulation of deformation velocity in each monitoring site are obtained by processing and analyzing the monitoring data. Through the analysis of index values, single factors model and multilevel models can be used in calculation in order to get the monitoring deformation magnitude.

There are three types of single factor model, namely cusp catastrophic model, coattail catastrophe model and butterfly mutation model. The normalization processing of monitoring data are carried out by cusp catastrophic using vector X and vector Y, coattail catastrophe using height variation, horizontal displacement vector and deformation speed of the current month, butterfly mutation using resultant vector X, resultant vector Y, accumulation of height variation and accumulation of horizontal displacement. The deformation analysis can be done using state variables based on complementary principle. The system of single-stage indicators, system of multi-step, calculation interface of all index, as shown in Figure 2-3.

Models of multi stage factors divided all effective indexes into two levels and evaluated the monitoring deformation amount with the combination of three kinds of models.

Program code is partly as follows :

```
…………..
For i = 1 To Me.ListView4.Columns.Count – 1‘butterfly mutation model
If Me.ListView4.Columns.Item(i).Text = str6 Then
For j = 0 To Me.ListView4.Items.Count - 1
sing1 = CSng(Me.ListView4.Items(j). SubItems(i).Text.ToString)
A3(j) = (Math. Abs(sing1)) ^ (1 / 2)
```

```
Next
End If
Next
…………..
Dim k3 As Single
For k = 0 To Me.ListView4.Items.Count - 1
Me.ListView3.Items.Add(Me.ListView4.Items(k).Text)
If bl = True Then
E3(k) = (B3(k) + A3(k) + C3(k) + D3(k)) / 4 'The princile of complementation
Else 'The principle of non-complementarity
………… 'Evaluating the minimum value
End If
Me.ListView3.Items(k).SubItems.Add(E3(k))
Next
```

(2) Evaluation model of slope mutation progression

To decompose the evaluation index of the slope stability, divide the control variables effected slope stability into four levels and two categories; internal factors and external factors. External factors are divided into three classes, namely: human activity, surface water and vegetation. Internal factors are divided into four classes, namely: the strength of the ground, slope geometry, physical conditions of the rock and engineering geology. Each class can be divided into several control variables. The formulae of the secondary index, third class index and state variable index as follows formulae 2-1, 2-2, 2-3.

The slope stability levels can be divided into 5 grades according to the statistical data, the calculation result and the practical experience, namely: the primary grade (ultra-stable, number 0.99 - 1), the secondary grade (stable, number 0.95 - 0.99), the third grade (moderately stable, number 0.9 - 0.95), the fourth grade (unstable, number 0.85 - 0.9) and the fifth grade (extremely unstable, between 0 - 0.85).

Formula of the secondary index

$$\begin{cases} C_1 = \dfrac{D_1^{\frac{1}{2}} + D_2^{\frac{1}{3}}}{2} \\ C_2 = \dfrac{D_3^{\frac{1}{2}} + D_4^{\frac{1}{3}}}{2} \\ C_3 = \dfrac{D_5^{\frac{1}{2}} + D_6^{\frac{1}{3}} + D_7^{\frac{1}{4}} + D_8^{\frac{1}{5}}}{4} \\ C_4 = \dfrac{D_9^{\frac{1}{2}} + D_{10}^{\frac{1}{3}} + D_{11}^{\frac{1}{4}} + D_{12}^{\frac{1}{5}}}{4} \\ C_5 = \dfrac{D_{13}^{\frac{1}{2}} + D_{14}^{\frac{1}{3}}}{2} \\ C_6 = \dfrac{D_{15}^{\frac{1}{2}} + D_{16}^{\frac{1}{3}}}{2} \end{cases} \quad 2\text{-}1$$

Formula of the third class index

$$\begin{cases} B_1 = \dfrac{C_1^{\frac{1}{2}} + C_2^{\frac{1}{3}} + C_3^{\frac{1}{4}} + C_4^{\frac{1}{5}}}{4} \\ B_2 = \dfrac{C_5^{\frac{1}{2}} + C_6^{\frac{1}{3}} + C_7^{\frac{1}{4}}}{3} \end{cases} \quad 2\text{-}2$$

Formula of state variable index

$$A = \frac{B_1^{\frac{1}{2}} + B_2^{\frac{1}{3}}}{2} \quad 2\text{-}3$$

RESULT AND DISSCUSS

Application to engineering

Overview of project site

Yunnan Xiaolongtan mine belongs to subtropical climate, with mean annual temperature 20°C. The rainy season is in May to September, which accounts for 70%~84% of annual precipitation. A larger earthquake in mining basin occurred in 1910,but the most disruptive earthquake happened in 1952, of which the seismic intensity was VII. There is tertiary exposure in mining basin. The old stratums exposure around is greenish-gray amygdaloidal omeishan basalt from old to new.

Application of monitoring data

The single-stage and multistage evaluation value can be calculated according to the monitoring data fromYunnan xiaolongtan mine, which is shown as follows:

The calculated results are as shown in Figure 4-5,in which the maximum of the deformation mainly concentrated near the monitoring point je11 and je12. The evaluation values of deformation can be obtained according to the monitoring values and experience, which are as follows :

TABLE 1 : The values calculated by coattail catastrophe model and butterfly mutation model.

Number	Cusp value	Coattail value	Butterfly value	Multi stage value
je11-1	0.234564	0.297064	0.339474	0.651559
je11-2	0.259769	0.441028	0.338504	0.724654
je11-4	0.950394	0.811798	0.913401	0.948974
je11-5	0.9211	0.808543	0.882546	0.944636
je11-6	0.902919	0.87827	0.939091	0.962969
je11-7	0.529691	0.480229	0.612147	0.806891
je12-1	0.32439	0.385564	0.439084	0.706509
je12-2	0.264886	0.336402	0.366331	0.66992
je12-3	0.602983	1	0.788057	0.938257
je12-4	0.448392	0.433004	0.494125	0.744474

(1) Stable, the catastrophe progression number is 0-0.4.
(2) Moderately stable, the catastrophe progression number is 0.4-0.65.
(3) Unstable, the catastrophe progression number is 0.65-0.8.
(4) Extremely unstable, the catastrophe progression number is 0.85-1.

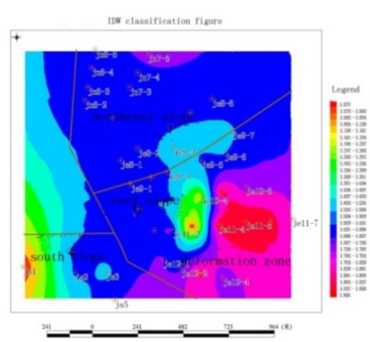

Figure 4 : Classification of IDW data

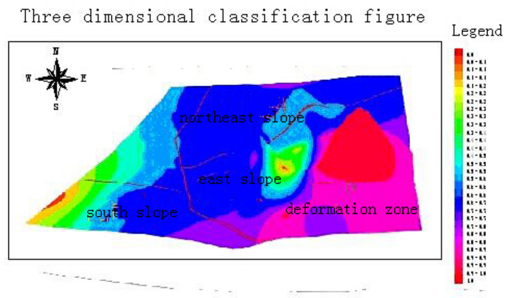

Figure 5 : 3D classification of IDW data

Total stability analysis of slope

1) The risk grades of the slope will be ranked by former data and expertise, namely: a-class, value: $0.99 \leq V < 1$, very stable; b-class, value: $0.95 \leq V < 0.99$, stable; c-class, value: $0.9 \leq V < 0.95$, moderately stable; d-class, value: $0.85 \leq V < 0.9$,instable stage, the deformation is obvious, measures should be implemented to protect the slope; e-class, value : $V < 0.85$,extremely unstable, the deformation is very obvious, measures should be implemented immediately to protect the slope.

2) The indexes are assigned by 17 evaluation index of the catastrophe progression, as listed in TABLE 2. The evaluation results can be visualized as shown in Figure 6 -7.

TABLE 2 : Index value of the catastrophe model

Indexes	The northeast slope	The east slope	The south slope
Feature of rock mass	3	3	3
Geology	2	3	2
Slopeheight (m)	140	150	90
Slope angle (°)	14	14	25
Rainfall (mm)	846	846	846
Seismic intensity	7	7	7
Cohesion (MPa)	0.024	0.024	0.024
Angle of Internal friction (°)	12	12	12
Underground water	2	3	4
Lakes and rivers	4	4	5
Ratio of water pressures in pore	0.25	0.25	0.25
Quality*g (kN·m-3)	18	18	18
Slope structure	4	4	4
Vegetation	4	4	4
Human engineering activities	5	5	4
Population density (persons/ km2)	100	100	100
Adverse geological condition	2	3	2

The monitoring data and the calculation result shown that the most dangerous area was in the east of the slope, where should be enhanced to monitor and treat the risks in time. The early risk warning of Xiaolongtan slope was carried out by both models of the mutation analysis and plane projection. The numerical results were obtained with a determinative calculation using the both models. The most reasonable result was made based on comparison of the results of two models, which can provide the foundation for early warning.

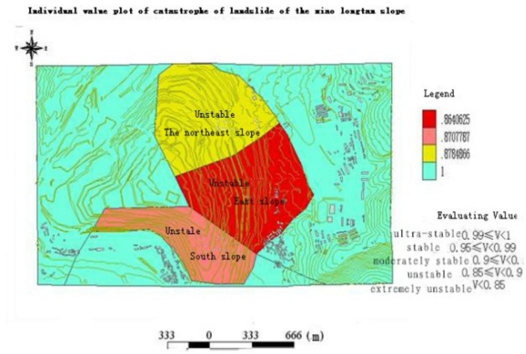

Figure 6 : Individual values of catastrophe

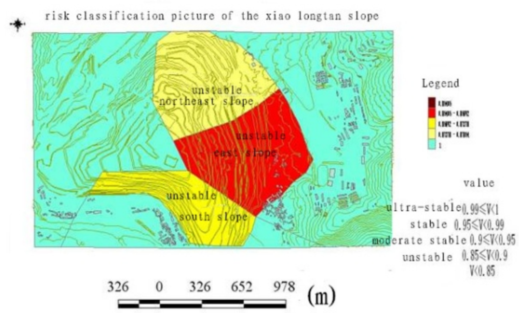

Figure 7 : Risk classification

CONCLUSIONS

As a new and reasonable method on slope stability evaluation, the application of mutation progression method is more and more wide. The realization of the computer program on mutation progression method can solve the mass problems on stability judgment and improve the efficiency and the correctness of the mutation values, which speed up the information process of the slope stability evaluation.

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