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A new method for spatio-temporal prediction of rainfall-induced landslide

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Abstract Geological condition and rainfall are two most principal conditions inducing landslides in the Chongqing region. By analyzing the forming conditions of rainfall-induced landslides, a new method for spatio-temporal prediction of rainfall-induced landslide is brought forward on the basis of grading and overlapping geological condition and rainfall factor in this paper. At first, semi-quantitative assessment and grading for the geological condition of a certain area or slope can be carried out with the multi-factor interactive matrix. Then the severity of rainfall in that area is grading according to the maximum daily rainfall and the total rainfall in a rainfall course. Finally, the “landslide probability judgement factor” can be worked out through grading and overlapping “geological condition influencing factor” and “rainfall influencing factor”, by which the landslide can be graded into 4 grades, they are landslide extremely easily happening, landslide easily happening, landslide difficultly happening and landslide hardly ever happening respectively. More accurate spatio-temporal prediction of rainfall-induced landslides can come true on the ground of detailed geological survey of some dangerous slopes in an area and more precise weather forecast. Finally, the reliability and feasibility of carrying out the spatio-temporal prediction of rainfall-induced landslides with the method of “two factors” grading and overlapping are validated by the example of Jipazi landslide.

Keywords: rainfall-induced landslide, geological condition, rainfall, two factors, grading and overlapping, interactive matrix, spatio-temporal prediction.

1 Introduction

The landslides influences on the human society have become an environment difficult problem not able to be neglected, and according to the priority of harms, harms of landslides are only smaller than those from earthquakes in all sorts of natural hazards^[1]. Landslide is part of rock mass, soil mass or their compound mass slides downward along a certain slid-

ing surface under the actions of inner and external dynamics, and it is one severe instability phenomenon of rock and soil masses. The Landslide induced by rainfall is called rainfall-induced landslide. Factors affecting the slope stability can be divided into two sorts: geological condition and external triggering factor. Geological condition mainly includes rock and soil masses structure, lithology, terrain, tectonic structure,

hydrogeological condition and ground stress, etc., which is the basic material condition and internal cause of landslide. External triggering factor chiefly includes slope dead weight, rainfall, temperature change, earthquake, external load, slope excavation and artificial blast, etc., which provides external dynamic condition for landslide. Most landslides occurred under the combined action of a specific geological condition and external triggering factor.

Landslide happens under the interactions and inter-coupling of lots of internal and external dynamic factors, whose forming mechanism is extremely complicated, furthermore, as the landslide usually happens suddenly and its movement pattern is indicative of uncertainty, the research of landslide prediction is far from higher precision^[2]. For the purposes of further understanding the forming mechanism and improving the prediction level of landslide, scholars at home and abroad have established some useful landslide analysis models from different viewpoints to attempt to predict landslides. For instance, by aid of experiments and practical experiences analysis, Japanese scholar Saito put forward the Saito Model of landslide prediction in 1968^[3]. On the basis of nonlinear characteristics of internal and external dynamics interactions in the process of landslide formation and the chaos theory, Qin Siqing *et al.* established a nonlinear landslide prediction model^[4–6]. Wang Zaiquan *et al.* obtained landslide information in terms of its time series of displacements, and established GM and Verhulst landslide statistics prediction model^[7,8]. In addition, numbers of scholars did deep researches on the landslide prediction model from the viewpoints of probability theory, fuzzy mathematics, information content and so on, and got remarkable improvements^[9–12]. Various landslide prediction models mentioned above have greatly aided the progress of landslide prediction research level, and lay a solid foundation for more accurate landslide prediction, but which are still far away from really and truly spatio-temporal landslide prediction.

The idiographic influencing degree of geological condition and rainfall on a certain landslide can be determined according to statistical analysis or expert-marking approach, but both of which exist some deficiencies. For instance, statistical method can analyze

the function of a certain factor in the process of landslide according to landslides historical data, but this method is only limited for single factor analysis, and does not synthetically consider the combined action of two or more factors. Taking the research by Ren Yourong as example, she adopted the theory of statistical analysis and used single factor analysis method to research the possibility of landslides, and assigned geological environment complexity and rainfall the values of 0.618 and 0.382 respectively^[13]. If this method is used to analyze landslide, it could not reflect the influences of interactions and overlapping between different factors, therefore, it could not reflect the real cause of landslide formation; expert-marking method includes too much personal subjective considerations, even marking the same landslide, different experts will analyze it from different viewpoints and obtain different marks. Therefore, there exist some limitations in two methods above, and they are unfit for extending.

On the basis of predecessors researches, taking rainfall-induced landslides in Chongqing region as research objects, a new method of rainfall-induced landslide prediction is brought forward through grading and overlapping “two factors” in this paper. Not only the internal cause—geological condition is considered, but also one of the most principal factors inducing landslides in Chongqing—rainfall is taken into account in this method, with which the slopes (especially dangerous slopes) sliding probabilities under the combined influences of geological condition and rainfall are researched. This research will be in favor of deeply understanding the landslide forming mechanism, and will also greatly improve the spatio-temporal prediction accuracy of landslide, as is significant to disaster reduction and prevention.

2 Landslide inducing factors analysis

The landslide forming mechanism is extremely complicated, which is formed under the combined actions of various internal and external dynamic factors. By concluding and analyzing data of landslides happened in some districts and counties of Chongqing, it is discovered that geological condition and rainfall are two of the most principal factors controlling the oc-

currence of landslide in Chongqing.

2.1 Geological condition

Chongqing is situated at east longitude $105^{\circ}17'$ — $110^{\circ}11'$ and north latitude $28^{\circ}10'$ — $32^{\circ}13'$, covering 80% area of the Three Gorges reservoir, where landslides happened frequently and severely. By statistical analysis of 129 landslides happened in Chongqing downtown area, Fuling, Wanxian, Yunyang and Fengjie, it is found that the landslides distribution of that region possesses the following characteristics:

(1) 87% landslides appeared on the slopes whose gradient are between 15° and 50° , and in which 81% landslides occurred on the slopes whose gradient are between 20° and 35° . 79% landslides happened on the slopes whose height is between 130 m and 200 m. 65% landslides are consequent landslides, and 35% landslides are anti-direction landslides.

(2) In all the landslides, the proportion of rock landslides is 22%, but their volumes are relatively larger, commonly being between one hundred thousands and millions cubic meters; The proportion of soil landslides is 78%, but their volume are relatively smaller, commonly being from thousands to one hundred thousands cubic meters.

(3) Most of large scale landslides happened in the rock layers in which sandstone and clay (or shale) interlay each other or in the relatively soft rock layers such as clay (or shale), marlstone and leaf limestone etc.

(4) 90% landslides happened at the places where the tectonic movement is strong, for example, fault zones, fold axes, syncline slots and the interjunction part of structure lines. Slopes with more faults, joints and cracks easily slide, and more landslides distribute at the concaves of rivers and valleys.

(5) Slopes in which underground water drainage is obstructed easily slides, and landslides are evidently affected by the action of underground water, spring water frequently appears at anterior borders of slopes or shearing rims.

The above distribution characteristics of landslides indicate that landslide formation obviously relates to geological condition, lithology, fault and joint, neotectonic movement, rock formation attitude, river erosion, underground water action and their interactions

and inter-couplings.

2.2 Rainfall

Researches indicate that rainfall, especially rainstorm, is the uppermost triggering factor of landslide under the condition of possessing terrain and geological conditions. According to investigations and statistics, 95% landslides in Wudu, Longnan region, Gansu Province, and 94% landslides Liupanshui, Guizhou Province, happened in rainy season^[13]. Consequently, it can be said that rainfall, especially heavy rainfall or rainstorm is one of the uppermost factor for inducing landslides among various external dynamics. The rainfall inducing functions mainly embody in the following aspects: slope dead weight increases when rainfall flows into slope; sliding surface is soaked and soften, and the shear resistant strength of slope will decrease when rainfall flows to underground and change into underground water; dry and wet alternation of slope causes rock and soil masses to rupture and results in large numbers of joints and fractures; it increases pore water press, and causes the slope being in limit equilibrium state to slide.

Only the water content in rock and soil masses of slope reaches a certain threshold, landslide is possible of happening in one rainfall course. Therefore, under a certain geological condition, the happening time of rainfall landslide is actually decided by both rainfall intensity and total rainfall in a rainfall course.

To study the relationship between rainfall and landslide, Landslides and rainfall data of many years in Chongqing downtown area, Fuling and Wanxian are collected in this paper. Research shows that the relationship between landslide and maximum daily rainfall (characterizing rainfall intensity) and total rainfall in a rainfall course is closest, For instance, from 15 to 30, July, 1982, there appeared 3 rainstorms in Yunyang county, Wanxian, and rainfall concentrated in 3 rainfall courses of 15 to 17, 19 to 22 and 26 to 30, in which the maximum daily rainfall reached 283 mm, and total rainfall reached 632 mm. These rainstorms resulted in more than 20,000 landslips and landslides in Yunyang county and more than 80,000 big and small landslips and landslides in the whole Wanxian region. In July and August, 1993, another rainstorm course happened in Wanxian, the total rainfall in July and August was

as much as 690 mm, accounting for 43.7% of annual rainfall. That rainstorm course induced 11,000 landslides in whole Wanxian region again, and the direct economic loss was as much as one hundred and eighty million RMB. Detailed analysis of 25 landslides happened in Fuling, 27 landslides happened in Chongqing downtown area and 36 landslides happened in Wanxian downtown area shows that rainfall-induced landslides account for 84%, 78% and 83% of those landslides respectively. In those rainfall-induced landslides, most happened in the middle and later stage of a rainstorm course or being late for several days, in which 95% landslides happened after rainstorm had started 10 hours, and 86% landslides happened after rainstorm had started 24 hours, and 81% landslides happened after rainstorm had started 24 hours to 72 hours, namely the second or third day after rainstorm had started. The time of landslide lagging behind the rainstorm is also related to geological condition and quality of slope and rainfall intensity, etc., but it usually does not exceed 10 days. It should be taken notice of that landslides is possible of sliding in that day when rainstorm starts at those places where the geological condition is quite poor and rainfall reaches 150 mm, and even more than 200 mm in a short period or within 24 hours.

Thus it can be seen that rainfall, especially rainstorm, is an important inducing factor of landslides happened in Chongqing region, and the maximum daily rainfall and total rainfall in a rainfall course are the uppermost influencing factors.

3 “Two factors” grading and overlapping and spatio-temporal prediction for rainfall-induced landslide

Researches on meteorologic early-warning for landslide are causing more and more attention, and practically applications of landslide meteorologic prediction have been carried out in lots of countries and regions. However, former researches on rainfall-induced landslide prediction mainly started from the rainfall viewpoint, and obtained experiential landslide prediction model through analyzing the relationship between rainfall (rainfall intensity, rainfall amount and rainfall duration) and landslides^[11–18], or determined

rainfall amount and rainfall intensity threshold for triggering landslides in a certain area by analyzing historical data in many years^[19,20]. Geological condition was hardly considered in those landslide prediction models, the reliability and accuracy of landslide prediction, therefore, was not so high.

3.1 Multi-factors interactive matrix

As geological condition involves numbers of influencing factors including terrain, lithology, fault and joint, neo-tectonic movement, river erosion and underground water and so on and their interactions and inter-overlappings, not only the involving factors are numerous, and their interactive and inter-overlapping mechanism is also quite complex, conventional methods are hardly possible of determining the special relationship between these influencing factors and the good or poor degree of geological condition. Consequently, the method of multi-factors interactive matrix is introduced in this paper for the purpose of semi-quantitatively assessing the geological condition of a certain area or slope under the combined actions of multi-factors.

Multi-factors interactive matrix is the core of rock engineering system (RES) approach^[21–24], by which not only the function of every influencing factor to the whole system can be determined, but also the functions of interactions between different influencing factors to the system are taken into account. This method is especially applicable to solving complex problems such as quantitative assessment for geological condition.

It can be seen from above research that in various geological conditions, terrain, lithology, fault and joint, neo-tectonic movement, river erosion and underground water closely relates to landslides happened in Chongqing region, thereby, these 6 influencing factors are selected to compose the multi-factors interactive matrix. The interactive matrix composed by the above 6 factors is illustrated in Table 1. In this interactive matrix, the sum of each row indicates the effect to geological condition for the actions exerted by the influencing factor situated at the principal diagonal on other influencing factors in this row (being called influencing weight of that factor), and which is placed in the right-hand column in Table 1; the sum of each

Table 1 Multi-factors interactive matrix for quantitative assessment of geological condition

Terrain	$V_{1,2}$	$V_{1,3}$	$V_{1,4}$	$V_{1,5}$	$V_{1,6}$	$\sum_{j=1}^6 V_{1,j}$
$V_{2,1}$	lithology	$V_{2,3}$	$V_{2,4}$	$V_{2,5}$	$V_{2,6}$	$\sum_{j=1}^6 V_{2,j}$
$V_{3,1}$	$V_{3,2}$	fault and joint	$V_{3,4}$	$V_{3,5}$	$V_{3,6}$	$\sum_{j=1}^6 V_{3,j}$
$V_{4,1}$	$V_{4,2}$	$V_{4,3}$	neo-tectonic movement	$V_{4,5}$	$V_{4,6}$	$\sum_{j=1}^6 V_{4,j}$
$V_{5,1}$	$V_{5,2}$	$V_{5,3}$	$V_{5,4}$	river erosion	$V_{5,6}$	$\sum_{j=1}^6 V_{5,j}$
$V_{6,1}$	$V_{6,2}$	$V_{6,3}$	$V_{6,4}$	$V_{6,5}$	underground water	$\sum_{j=1}^6 V_{6,j}$
$\sum_{i=1}^6 V_{i,1}$	$\sum_{i=1}^6 V_{i,2}$	$\sum_{i=1}^6 V_{i,3}$	$\sum_{i=1}^6 V_{i,4}$	$\sum_{i=1}^6 V_{i,5}$	$\sum_{i=1}^6 V_{i,6}$	$\sum_{i=1,j=1}^6 V_{i,j}$

column indicates the effect to geological condition for the actions exerting on the factor situated at the principal diagonal by other influencing factors in this column (called influenced weight), which is placed in the lowest row in Table 1.

For the sake of quantitatively describing the relationship between different landslide influencing factors and their interactions and geological condition, geological condition is graded into 4 grades according to the influence of all factors and their interactions, and representing it with 0–3 respectively: 0 indicates factors and their interactions have no influence or basically have no influence on geological condition; 1 indicates factors and their interactions have a certain influence on geological condition, but the influencing intensity is not high; 2 indicates factors and their

interactions have a strong influence on geological condition; and 3 indicates factors and their interactions an extremely strong influence on geological condition. Values of influencing factors on the principal diagonal denote the influences of the factors themselves to geological condition, whose value assignment is shown as Table 2.

The geological condition of a region or slope can be calculated in terms of formulas (1) to (3):

$$S = \sum_{i=1,j=1}^n V_{i,j} \tag{1}$$

$$F = S_{\max} \tag{2}$$

$$FEG = \sum_{t=1}^n S / (2F) \times 100\% \tag{3}$$

In these formulas, variation n indicates the number

Table 2 Grading and value assignment of influencing factors

Terrain		Lithology		Fault and joint	
Slope range (°)	Value assignment	Rock hardness	Value assignment	Dense degree	Value assignment
$0 \leq S < 10$	0	soft	0	sparse	0
$10 \leq S < 30$	1	softer	1	middle	1
$30 \leq S < 50$	2	hard	2	dense	2
$S \geq 50$	3	extremely hard	3	extremely dense	3

Neo-tectonic movement		River erosion		Underground water	
Average rate V (mm/a)	Value assignment	Erosion degree	Value assignment	Erosion degree	Value assignment
$V < 5$	0	poorer	0	poorer	0
$5 \leq V \leq 10$	1	middle	1	middle	1
$10 \leq V \leq 15$	2	strong	2	strong	2
$V > 15$	3	extremely strong	3	extremely strong	3

of influencing factors (here $n = 6$), and variation t indicates the number of slopes in a region, whose value range is from 1 to n . S is the sum of all factors in the matrix, and it denotes the influencing intensity of all factors and their interactions to geological condition. F indicates the sum of all factors in the matrix when each $V_{i,j}$ is equal to 3 (that is to say when the influences of factors and their interactions are all extremely intense). Variation FEG denotes the good or poor degree of the geological condition of a region or slope, being called “geological condition assessment factor”.

The bigger the “geological condition assessment factor” FEG value of a region or slope is, the more intense the influences of various factors and their interactions to the geological condition are, consequently, the poorer the geological condition is.

3.2 Method of “two factors” grading and overlapping

The relationship between geological condition and rainfall and landslide is researched through “two factors” (namely geological condition and rainfall) grading and overlapping method in this paper. This method avoids directly analyzing the idiographic influence of each factor on a landslide, but synthetically considers the combined influence of geological condition and rainfall. The relationship between geological condition and rainfall and landslides can be researched through formula (4):

$$F_{LHP} = F_G \cdot F_R. \quad (4)$$

In this formula, F_G quantitatively denotes the influence of geological condition on landslide, being called “geological condition influencing factor”; F_R quantitatively denotes the influence of rainfall on landslide, being called “geological condition influencing factor”; F_G and F_R go by the general name of “landslide inducing factor”; F_{LHP} denotes the combined influence of two landslide inducing factor on landslide, indicating the landslide possibility (or slope stability), and is called “landslide possibility judgement factor”.

In order to quantitatively describe the relationship between each landslide inducing factor and landslide, geological condition and rainfall are graded according to their good or poor degree and severity respectively,

and two corresponding landslide inducing factors are assigned values. By statistically analyzing the principal geological conditions of landslides happened in the Chongqing region, the geological condition is graded in terms of the method of multi-factors interactive matrix. By statistically analyzing historical rainfall data and 88 landslides data in the Chongqing downtown area, Fuling and Wanxian, rainfall is graded in light of probability method. According to the good or poor degree, geological condition is graded into 5 grades, being extremely good, good, middle, poor and extremely poor respectively, correspondingly, the “geological condition influencing factor” F_G is assigned to the value of 1 to 5 respectively. Because maximum daily rainfall and total rainfall in a rainfall course are two most important indices for influencing landslide, both of them are used to indicate the rainfall severity in this paper, on the basis of which the rainfall is graded into 5 grades, being extremely light, light, middle, serious and extremely severe respectively, correspondingly, the “rainfall influencing factor” F_R is assigned to the value of 1 to 5 respectively. Assigning F_G and F_R to the value of 1 to 5 indicates that the influence of these two landslide inducing factors on landslide is from extremely light to extremely intense. Two landslide inducing factors grading and value assignment are as shown in Table 3.

3.3 Spatio-temporal prediction of rainfall-induced landslide

By grading and overlapping two landslide inducing factors, namely “geological condition influencing factor” and “rainfall influencing factor”, the landslide possibility under the combined action of these two influencing factors can be analyzed in detail, that is to say, according to the value of “landslide possibility judgement factor” F_{LHP} , the landslide possibility of a certain region or slope can be determined, therefore, the landslide prediction can be carried out. The landslide is graded into 4 grades according to their possibility, and they are landslide extremely easily happening (IV), landslide easily happening (III), landslide difficultly happening (II) and landslide hardly ever happening (I) respectively.

For the sake of statistical analysis, the author researches 24 rainfall-induced landslides happened in Chongqing region in detail, and built a multi-factors

Table 3 “Landslide inducing factor” grading and value assignment

Geological condition	“Geological condition assessment factor” F_G	“Geological condition influencing factor” F_G	Influence of rainfall on landslide	Maximum daily rainfall (mm)	Total rainfall in a rainfall course (mm)	“Rainfall influencing factor” F_R
Extremely good	0–20%	1	Extremely light	0–20	Less than 50	1
Good	20%–40%	2	Light	20–50	50–100	2
Middle	40%–60%	3	Middle	50–100	100–150	3
Poor	60%–80%	4	Serious	100–150	150–250	4
Extremely poor	80%–100%	5	Extremely serious	Over 150	More than 250	5

interactive matrix for every landslide. Through researching the relationship between “geological condition influencing factor” F_G and landslide possibility, it is found that only 1 landslide happened when the value of F_G is less than 3, namely when the geological condition is extremely good or good, here the landslide possibility is 4.2%; when the value of F_G exceeds 3, landslide possibility is 95.8%, as shown in Fig. 1. These illuminate that most of landslides happened when the geological condition of a slope is extremely poor, poor or middle, and landslide hardly ever happens when the geological condition of a slope is extremely good or good. Through researching the relationship between “rainfall influencing factor” F_R and landslide possibility, it is found that only 1 landslide happened when rainfall is extremely light or light (namely F_R is equal to 1 or 2), but 23 landslides happened when rainfall is extremely severe, severe or middle (namely F_R is equal to or greater than 3), as shown in Fig. 2. Consequently, when calculating “landslide possibility judgement factor” F_{LHP} , we only take the circumstances of F_G being equal to or greater than 3 and F_R being equal to or greater than 3 into account, and take the circumstance of F_{LHP} being less

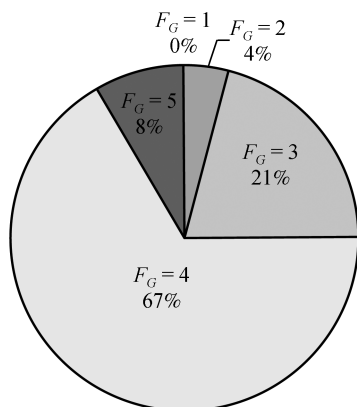


Fig. 1. Relationship between “geological condition influencing factor” F_G and landslide probability.

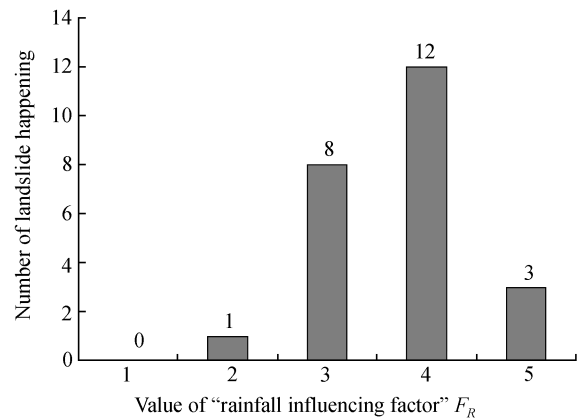


Fig. 2. Relationship between “rainfall influencing factor” F_R and landslide happening numbers.

than 9 (namely F_G is less than 3 and F_R is less than 3) as landslide hardly ever happening (I) and do not consider. Here, according to formula (2), there only 6 circumstances for the value of F_{LHP} , being 9, 12, 15, 16, 20 and 25. By researching 23 landslides conforming to the requirements of F_G is equal to or greater than 3 and F_R is equal to or greater than 3, it is found that there exists the relationship as shown in Table 4 between F_{LHP} and landslides happening numbers and possibility.

It can be seen from Table 4 that under the condition of F_G being equal to or greater than 3 and F_R being equal to or greater than 3 landslide possibility is very high when any of F_G or F_R is equal to or greater than 4, and landslide possibility has reached 87.5%. When F_{LHP} is equal to or greater than 12 and equal to or less than 15, landslide possibility reaches 25.0%, and when F_{LHP} is equal to or greater than 16 and equal to or less than 25, landslide possibility reaches 62.5%. These show that the poorer geological condition is, and the more severe rainfall of a region is, the more possible of happening landslide in that region. F_G being equal

Table 4 Relationship between “landslide possibility judgement factor” F_{LHP} and landslide possibility

Landslide	F_{LHP} value					
	$F_{LHP}=9$	$F_{LHP}=12$	$F_{LHP}=15$	$F_{LHP}=16$	$F_{LHP}=20$	$F_{LHP}=25$
Number of landslide happening time	2	6	3	10	1	1
Landslide happening frequency	8.33%	25.00%		62.50%		
Landslide possibility	Landslide difficultly happening (II)		Landslide easily happening (III)		Landslide extremely easily happening (IV)	

to 5 or F_R being equal to 5 is an extreme situation, aiming at this situation, we selected and researched 8 landslides confirming to this condition in the Chongqing region. The research shows that under the condition of F_R being equal to 5 all landslides had happened when the geological condition of a slope is middle, poor and extremely poor, and under the condition of F_G being equal to 5 all landslides had happened when rainfall is middle, severe and extremely severe. Thereby, the situation of F_G being equal to 5 or F_R being equal to 5 (that is to say F_{LHP} is integer multiple of 5) is graded into landslide extremely easily happening (IV) in Table 4.

It is well known that the precision of nowadays weather forecast is very high, the rainfall in the following several days or weeks can be accurately predicted. Thus accurate F_R value can be obtained according to the above mentioned method. For the sake of reducing and preventing disaster, some dangerous slopes, especially some ancient landslides, can be researched with emphasis. Through geological reconnaissance, we can build multi-factor interactive matrix for each dangerous slope, and then calculate the value of their “geological condition assessment factor” FEG , and finally obtain the value of “geological condition influencing factor” F_G . In terms of formula (4), the value of “landslide possibility judgement factor” F_{LHP} can be worked out. Adopting the above mentioned method, the landslide possibility of these dangerous slopes can be judged, that is to say we can predict the landslide possibility of these dangerous slopes. The spatial range of landslide is determined by these dangerous slopes themselves, and the happening time of landslide is determined by rainfall, consequently, using “two factors” grading and overlapping method to predict rainfall-induced landslide realizes genuine spatio-temporal landslide prediction.

4 Example analysis of landslide

Here the Jipazi landslide happening in Yunyang County, Chongqing, is taken as an example to study the relationship between geological condition and rainfall factor and landslide, furthermore, the feasibility of carrying out the spatio-temporal prediction of rainfall-induced landslides with the method of “two factors” grading and overlapping is discussed.

Jipazi landslide is situated at the north bank of the Yangtze River, about 1 km east of Yunyang County seat, which is a part of ancient Baota landslide. From 17 to 18 July, 1982, the slope began to slide and collapse, whose total volume was about 15,000,000 cubic meters. About 2,300,000 cubic meters soil and rock compound body at its anterior part slid into the Yangtze River, and raised riverbed 30 to 40 m, which resulted in extremely serious economic losses.

4.1 Geological condition and rainfall in landslide area

This landslide developed at the north flank of Guling syncline in the east Sichuan fold belt. This area is full of numerous escarpments, ridges and grooves interlace, and there are series of landslide cracks and fourth order tablelands. In this area, emerging rocks belong to mudstone mixing a little quartz sandstone of Suining group, quartz sandstone, feldspathic quartz sandstone and interbedding mudstone of Peilai town group in upper jurassic system, and the rock formations abound with tensile cracks, squeezing cracks and torsion cracks^[26]. The landslide body as a whole maintains three layers structure of ancient Baota landslide, which consists of powder clay containing calcic nodule, powder rock and soil mixed with crushed stones and block stones, and layered broken rock formation from top to bottom. Rocks are broken and

loose, with lots of cracks. The southern part of landslide is close to the Yangtse River, eastern and western parts are deeply cut by the Dahe valley and the Tangxi River flowing from north to south, and forms a consequent bank slope. The slope top height is 716 m, more than 600 m higher than low water level of the Yangtse River. The underground water supplying condition of the bank slope is poor, drainage condition is good, and underground water is relatively poorer, which basically does not affect the slope stability.

In mid July, 1982, there appeared an especially heavy rainstorm. Rainfall had reached 377.4 mm only in 16 and 17, in which rainfall reached as much as 199.3 mm in 16. Rainfall reached 269.1 mm in 28 hours from 4 o'clock in 16 to 8 o'clock in 17. Rainfall reached 333.1 mm to 2 o'clock in 18 when the slope started to slide tempestuously. Much of rainfall seeped into the broken and loose slope, resulting in the sliding zone being saturated with water, whose shear resistant strength signally declined, and finally caused the slope to become instable and to slide tempestuously.

4.2 Landslide stability judgement

A multi-factor interactive matrix consisting of terrain, lithology, fault and joint, neo-tectonic movement, river erosion and underground water can be built to assess the geological condition of Yunyang Jipazi landslide, as shown in Table 5.

In terms of formulas (1) to (3), the geological condition of studying area can be semiquantitatively assessed. By calculating, the value of "geological condition assessment factor" FEG is 50.7%, according to the judgement method in Table 3, here the value of F_G should be 3, that is to say the geological condition of studying area is middle. If weather forecast could accurately predict that especially heavy rainstorm happened in Yunyang in 16 July, and that the maximum daily rainfall will exceed 150 mm, and the total rainfall will exceed 250 mm in this rainfall course, then

the value of F_R could be predicted to be 5 according to the judgement method in Table 3. In terms of formula (4), it can be worked out that the value of F_{LHP} is 15. Referring to the landslide possibility judgement method, at this time the slope stability is extremely poor, and this slope belongs to the grade of landslide extremely easily happening (IV). It can be seen from this that Jipazi landslide being extremely possible of happening in this rainstorm course can be predicted as long as the maximum daily rainfall and the total rainfall in this rainfall course can be accurately predicted. With the improvement of weather forecast, accurately predicting rainfall-induced landslides is becoming more and more possible.

The example analysis of Yunyang Jipazi landslide proves that it is completely feasible to accurately predict the happening time and place of rainfall-induced landslide with the "two factors" grading and overlapping method.

5 Conclusions

The following conclusions can be derived from the research in this paper:

(1) "Two factors" (namely geological condition and rainfall) grading and overlapping method is a new model for accurately predicting happening time and place of rainfall-induced landslide. Not only the rainfall-induced landslide possibility can be semiquantitatively assessed by "landslide possibility judgement factor", but also the judgement principle is simple, the use of it is convenient, and landslide prediction precision is high.

(2) The geological condition of a certain region involves lots of factors such as terrain, lithology, neo-tectonic movement, fault and joint and hydro-geological condition etc., which is influenced not only by these factors themselves, but also by their interactions and inter-overlappings. The multi-factors interactive

Table 5 Interactive matrix for quantitative assessment of geological condition

Terrain 2	1	3	1	3	3	13
2	lithology 3	3	0	2	3	13
3	3	fault and joint 2	2	3	3	16
3	3	3	neo-tectonic movement 1	2	2	14
2	2	2	1	river erosion 2	1	10
2	2	1	0	1	underground water 1	7
14	14	14	5	13	13	73

matrix synthetically considers the influences of every influencing factor itself and the interactions between different factors to the whole system, therefore, using it to semiquantitatively assess the geological condition of a certain region or slope will get more objective and reliable result.

(3) By laying a strong emphasis on the research of the geological conditions of some dangerous slopes (including ancient landslides), combined with more accurate weather forecast, landslide possibility of these dangerous slopes can be predicted with relatively higher precision. The distribution of these dangerous slopes fixes the spatial places of landslides, and accurate rainfall forecast decides the happening time of landslides, consequently, the semiquantitative spatio-temporal prediction for rainfall-induced landslide can really come true with the “two factors” grading and overlapping method, as is in possession of great scientific significance and higher practical value.

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