Research progress in loess landslides forecast and prediction based on assimilating multi-source information

Xuejiao Bai1,2,3, Lingzhi Sang1, Guichen Bai4, Hongxia Kang1, Zhen Liu4

1China Transport Telecommunications & Information Center, Beijing 100011, China
2National Engineering Laboratory for Transportation Safety and Emergency Informatics, Beijing 100011, China
3Faculty of Education, Beijing Normal University, Beijing 100875, China
4Kangbao Transportation Bureau, Zhangjiakou 076650, China

* Xuejiao Bai: baixuejiaoz@126.com

Abstract. China’s one-third western region disseminated in Qinghai, Ningxia, Shaanxi, Gansu and other provinces witnessed landslide disasters in recent decades over loess and loess-like soils with special composition and properties. Loess landslides occur more frequently with serious constrained in the development of regional economy following the sharp increase in human engineering activity, especially from the launch of China’s Grand Strategy of Developing the West region of China. Therefore, the loess landslide forecasting and prediction is a hot topic in the study of environmental geology. This research demonstrates the situation and progress of the landslide forecasting and prediction motivated by the theoretical methods and technological means of landslide forecasting and prediction, the study of remote sensing survey of landslides, the study of multi-source information fusion and the study of loess landslide forecasting and prediction, followed by the prediction model for loess landslide based on assimilating multi-source information with its specific technology route anticipation based on assimilating multi-source information.

1. Introduction

Landslides, which destroy forests, farmland and houses, harm humans and animals, destroy roads and various infrastructures, causing serious harm to national economic and social development, are common geological disasters in China. The annual direct economic loss caused by geological disasters such as landslides is about 20 billion yuan, and the indirect losses are even more incalculable [1]. Under the condition that it is impossible to carry out protection engineering treatment for all potential disaster points, disaster prevention and mitigation measures can be taken as early as possible to minimize disaster losses if the occurrence and development of landslides can be accurately predicted. Therefore, the research on landslide forecasting is a hot issue in the field of environmental geological research and landslide hazard research, and has important theoretical significance and practical application value. Landslide prediction research is to make scientific, quantitative and accurate assessment and prediction analysis of the possibility and occurrence of landslide occurrence and its location and scale.

Landslide prediction is one of the main directions and objectives of landslide research, and is also a difficult problem in the world. In 1965, Saito proposed time prediction formula of landslide instability, which pioneered the research on prediction of landslide disasters [2]. Since then, domestic and foreign scholars have carried out a lot of research on theoretical research and technical means of landslide
forecasting. (1) From the theoretical research of landslide prediction and forecasting, it has passed three important stages, the first stage is relies on the analysis of geological phenomena and the prediction of empirical models under ideal conditions, the second stage is to study the displacement-time curve trend of the fitted landslide to construct a prediction model, and the third stage is to construct the nonlinear dynamics model based on system theory and nonlinear science. At present, the landslide predicting and forecasting theory has entered the stage of comprehensive forecasting based on multi-source information that combining traditional forecasting techniques with current numerical forecasting techniques. And linear grey model, fuzzy mathematics, fractal model, artificial neural network and other landslide prediction models have been developed in different stages [3–5]. (2) The most common and effective method for predicting landslides is to use some factors which affect the occurrence and development of landslides to investigate and monitor landslides. Therefore, the progress of landslide predicting and forecasting techniques is mainly reviewed from the acquisition methods of landslide key factors and the development of data processing methods. With the development of aerospace earth observation technology, computer technology and electromagnetic wave information transmission technology and the gradual maturity of its analysis and processing methods, landslide predicting has been carried out from conventional geological survey methods and sophisticated monitoring methods to the use of aerospace technology and internet of things technologies acquires hazard factors, and to comprehensively utilize the information acquired by multiple platforms to meet the different application requirements and different precision. This paper reviews the progress of loess landslide predicting based on remote sensing (multi-source information fusion), and reviews and summarizes the literature from landslide predicting and forecasting, loess landslide predicting research and landslide hazard remote sensing investigation.

2. Researches of landslide predicting and forecasting

2.1. Theory research of landslide predicting and forecasting

Landslides have its own characteristics of complex development conditions, varied triggers and diverse types, so it is a worldwide difficult problem to accurately predict landslide, and it is also the main direction and goal of landslide disaster research. In 1965, Saito proposed the prediction formula for landslide instability time, which pioneered the research on forecasting landslides [2]. Subsequently, Saito have proposed a differential equation based on the three-stage theory of landslide creep damage to establish the accelerated creep of the evolution process, and then successfully forecasted the Gaotangshan landslide in Japan. However, these methods were based on geological phenomena and empirical analysis under ideal conditions, and ignored the mechanism of landslide occurrence and movement, so the prediction model is prone to large errors. In the 1980s, with the introduction of the International Natural Disaster Reduction (INDR), scholars from all over the world were encouraged to predict natural disasters such as landslides. They have studied landslide predicting and forecasting model by establishing the trend in the relationship between landslide displacement, occurrence time and certain factors. Liu [3] have proposed a method for simulating the creep characteristics of landslides by a nonlinear grey model, and observation data of Xintan landslide in the Three Gorges of Yangtze River was used to verify its possibility of application to predict landslide. Jade et al [6] constructed a statistical model for regional landslide hazard assessment for the 66km² area of Alkananda Valley based on information theory and regression analysis. In addition, scholars have also introduced fuzzy mathematics, graphic methods, biological growth models, etc. for establishing landslide predicting model [4,7]. The above methods can't respond well to the dynamic change characteristics of landslide for they does not consider and eliminate the influence of interference factors and redundant information. It is a transition period from qualitative research to quantitative research to integrated quantitative and qualitative research. With the development of various new data processing technologies, a series of landslide synthetically forecasting models and criteria based on system theory and nonlinear science, such as nonlinear dynamic model, random forest model and support vector machine model, were summarized by domestic and foreign scholars. Ma et al [8] constructed the support vector machine...
model of landslide predicting using DEM and remote sensing data in Qingyuan country, and results consistent with the actual landslide. Goetz et al [9] applied logistic regression, generalized additive models (GAM), weights of evidence (WOE), random forest classification (RF) and other techniques to construct a landslide predicting model to analyse the landslide susceptibility of three regions in Austria, and to analyse the predictive performance of different methods by Cross-validation method.

2.2. Technical means researches of landslide predicting and forecasting

From the perspective of technical means, landslide predicting has been carried out from conventional geological survey methods and sophisticated monitoring methods for landslide investigation and empirical forecasting to the use of aerospace technology and internet of things technology for hazard factor acquisition, and to the landslide comprehensive predicting system stage using computer data processing technology based on GIS platform. In the early days, scholars mainly studied the geotechnical combination characteristics, their deformation and strength to establish a slope instability prediction model through conventional geological surveying and surveying. Sassa Kyon have successfully predicted the slip distance in practical applications using the functional conservation theory based on the parameters obtained from the ring shear experiment. Yin et al [10] have established a slope instability predicting model through introducing information content and regression analysis of two-state variable based on slope engineering geological mapping and laboratory analysis, and discussed the regional landslide law of the Xunyang section of the Hanjiang River valley. With the development of 3S, the landslide monitoring and early warning based on remote monitoring technology has also made great progress, and more monitoring results are applied to landslide predicting. Hu et al [11] have discussed the landslide spatial predicting method using geographic information system (GIS) and remote sensing (RS) to acquire and manage landslide information which included slope and landform types in the Cameron Highlands of Malaysia. Wang et al [12] proposed the theoretical concept and key methods of “digital landslide” based on advanced information technology in early stage of landslide in China, which provided a valuable foundation for the study of storm landslide warning and monitoring model. In recent years, with the significant progress in the fields of launch vehicles, sensors and computer data processing, landslide forecasting has entered a comprehensive and dynamic forecasting stage with a variety of technical means. Kong et al [13] have used multi-source temporal and spatial information of land surface and the main factors of landslide lithology and slope structure obtained from the multi-sensor networks as the identification indicators to construct the comprehensive identification model of control factors based on different sources in the Wenchuan earthquake-stricken area, which provided a basis for early identification and prediction of landslide hazards. Wang et al [14] have developed a landslide predicting system using the data of disaster geological map and information obtained from landslide predicting model in professional monitoring and forecasting criteria, and this system have been demonstrated in Badong New Town and the typical landslide of Bazimen and Baishuihe. At the same time, for the shortcomings of long interpretation and poor repetitiveness based on statistical methods combined with manual interpretation, scholars have studied landslide key factors analysis and model by combining advanced data processing techniques such as fuzzy theory, neural network, support vector machine, wavelet analysis, etc., which can more realistically reproduce the influence of its geographical position and slope, aspect and geological environment, and enhance the ability of prediction. Cao et al [5] have constructed a time-space predicting model for considering the rainfall intensity, the previous rainfall and the underlying surface based on the susceptible index and BP nerve network on GIS, and studied the rainfall-type landslide in Yucheng District of Ya'an City, which predicting accuracy have reached 90%.

3. Researches of the loess landslide predicting and forecasting

One-third of landslide disasters in China occur in provinces with loess and loess-like soils such as Shaanxi province, Gansu province and Shanxi province, which bring great harm and threat to local production and construction and people's lives and property. Loess landslides have the characteristics of general landslides, and are distinguished from the general landslides due to the unique structure of
loess. They have their specific mechanisms of occurrence, development and evolution, which have attracted wide attention of scholars. Especially for the spatiotemporal predicting and forecasting of loess landslides, scholars have done a lot of research and achieved many valuable results in prediction theory and technical means in practical applications. In the fall of 1981, Fengxian, Liuba, Lueyang, Ningqiang and other counties in the southwest of Shaanxi Province have caused landslides and mudslides of about 20,000 due to heavy rains, which causing heavy losses to the state property and people's lives. Wu [15] have discussed the formation conditions and preventive measures of the loess landslide based on the field investigation of the county disaster area by the Shaanxi Bureau of Geology and Mineral Resources. Song et al [16] have given the relationship between the occurrence time of loess landslide and creep rate, creep rate and creep of landslide by studying the formation factors, characteristics and mechanism of loess landslide based on field investigation and experimental research, this result have provided a reference for loess landslide predicting.

As scholars delve into the research of loess landslide predicting and forecasting, more and more mathematical methods and theoretical models have been introduced into the construction of loess landslide prediction model. Cui et al [17] have reversed the mechanical parameters of the slope foundation using the finite element back analysis method based on the deformation monitoring results of loess landslide and the initial strain distribution of the slope, which provided a reliable basis for loess landslide predicting. Li et al [18] have proposed the spatial prediction theory of loess landslide considering the slipping conditions through combining with more than 50 typical loess landslide hazard case studies based on a large number of tests on the mechanical properties of loess, and have successfully carried out spatial predicting in many places in Gansu Province. The considering and applying of sliding condition of landslide body and the mechanical strength parameters of loess can reflected the mechanism characteristics of loess landslide and greatly improved the accuracy of loess landslide predicting. It has wide application value in the field of loess landslide predicting and forecasting. The introduction of statistical mathematics has brought great vitality to the study of loess landslide predicting and forecasting. Many prediction modeling methods are all based on statistics and logic. Aiming at the characteristics of typical loess landslides, Wang et al [19] have established a slip predicting model with high accuracy and extensive practicability by collecting 20 sets of data related to the sliding distance of landslides based on the theory of multiple regression analysis. Li et al [20] have proposed the spatial predicting indexes, influence factors and modelling idea of four typical landslides of faulted landslides, high-speed and long-range landslides, low-speed and slow-moving landslides and landslide-mudflows based on investigating the formation conditions and kinematics of a large number of landslides, this have provided ideas and basis for spatial prediction modelling of landslide hazards in the loess area.

The development trend of predicting and forecasting modelling of loess landslide is to use a higher level method to improve the accuracy. With the development of computer technology and data processing technology, many data mining methods have been applied to the prediction of loess landslide prediction. Scholars have opened the application of higher-level algorithms such as neural network, fuzzy theory, support vector machine and wavelet analysis in loess landslide predicting modelling. Yang et al [21] have established a BP neural network predicting model for the slip zone of loess landslide in the dense loess landslide along the Longhai Railway, and proposed a new practical and efficient prediction method for the seismic subsidence coefficient, which have important value and application prospects in the stability evaluation of landslide and the analysis of railway foundation settlement. Li et al [22] have proposed a loess landslide displacement predicting method called WA-BT-ELM based on wavelet analysis (WA), boosting regression tree (BT) and extreme learning machine (ELM) method, and have predicted the landslide displacement based on the monitoring data of the Heifangtai landslide, which effectively improved the accuracy of the loess landslide predicting.

Due to the complex development conditions of landslides and the variety of inducing factors, the widely used two-dimensional models cannot fully consider the three-dimensional spatial changes of soil structure, soil properties, stratum structure, groundwater and other geological environment factors, thus it may not match the actual scenes of the loess slopes. Therefore, some scholars have begun to explore the use of models that can consider the three-dimensional spatial variation of complex loess slope...
geological environment to evaluate the stability of loess landslides, which is of great significance for obtaining accurate evaluation and prediction results. Hong et al [23] have measured the calculation parameters and carried out the three-dimensional numerical simulation and spatial predicting of the Sanyuandong loess landslide in Lishan, Xi’an, Shaanxi Province through the large-scale ring shear experiments on different parts of the actual landslide sliding path based on the Sassa landslide motion simulation model, and results shows the model has good applicability. Xin et al [24] have used Scoops3D model to predict the stability of typical loess gully landforms in Huachi County, Gansu Province and the landslide stability of a large number of shallow loess landslides using the digital elevation model (DEM) data with different resolutions, and the stability of shallow loess landslides in the gully region was effectively predicted.

4. Researches of the loess landslide predicting and forecasting

4.1. Researches of the remote sensing survey of landslide hazard

With the gradual deepening of landslide research, scholars have gradually realized that due to the complexity of landslide development and the occurrence of geological environment, breeding conditions, genetic types and influencing factors, the conventional geological survey methods were often difficult to achieve real-time and had the disadvantages of high labor intensity, single monitoring index and low precision, and the precision monitoring methods required the use of precision equipment, which is costly and subject to many external conditions. After the 1950s, with the significant development and progress in the fields of launch vehicles, sensors and digital processing, domestic and foreign scholars began to use remote sensing techniques such as aerial photography and land satellite to study the geological environment, spatial distribution and development trend of landslide areas. In 1955, China applied the aeronautical geological method to the railway survey of the Lanxin line for the first time, and in the following two years, the bedrock landslide and the landslide of the Jinsha River on the Chengkun line were surveyed by aerial visual flight and aerial photo interpretation and mapping. In the 1970s and 1980s, domestic and foreign scholars mainly used satellite data such as multi-temporal aerial photographs, Landsat, and SPOT for landslide hazard monitoring, identification, and zoning. Sauchyn et al [25] have used Landsat remote sensing images to study the tonal and strip characteristics of some landslides in Colorado. Lei and Wang have completed remote sensing surveys of landslides on railway lines such as Beijing-Guangzhou, Yunnan-Tibet, Sichuan-Tibet and Nankun railways, which provided basic data sources for investigating the distribution of landslide hazards along the railway [26, 27]. In the 1990s, domestic and foreign scholars began to use thermal infrared data, interference radar, etc. to conduct landslide hazard identification and classification, and disaster sensitive area analysis. Singhroy et al [28] have used SAR and Landsat TM images to identify landslides in the Saskatchewan River and the Ottawa Valley in Canada, and obtained a landslide risk assessment map. Chinese scholars Sun and Niu have used remote sensing survey techniques to identify landslides along the railways such as the Longhai Railway, the Neijiang-Kunming Railway, the Sichuan-Tibet Highway, and the Huihang Expressway, to produce regional landslide distribution maps and to identify landslide micro-geotype types. The study provides a data foundation for railways, highway selection and disaster prevention projects [29, 30].

4.2. Researches of landslide predicting and forecasting based on multi-source information fusion

With the development of the earth observation technology of remote sensing, remote sensing data developed towards multi-source, multi-band and high resolution data, a global earth observation system with different resolutions, all-weather and multiple levels has been established, which constitute multi-source data for the same region in spectrum, direction and polarization. This greatly satisfied the dynamic monitoring of landslide remote sensing with different application requirements and different precisions. In order to make more efficient use of multi-source information, scholars have done a great deal of work in integrating information from different resolutions of sensors on different satellites, aircraft and ground platforms, this facilitated the application of multi-source data in landslide predicting. Gupta et al [31] have used GIS spatial overlay analysis to map the landslide hazard in the Himalayas.
based on multi-source data such as aerial photos, MMS data, false color composite images and various field data. Pradhan [32] have used multiple logistic regression coefficients to analyze the landslide hazard in Penang, Cameron and Sailand in Malaysia through extracting spatial factors affecting landslide occurrence from aerial photographs, SPOT 5 and TM data. With the development of multi-return and full-wavelength LiDAR technology, it is a development trend of landslide research to identify and monitor landslides by extracting feature from the fusion data of multi-source optical images, SAR images and LiDAR data with high penetration capability. Chen et al [33] have used likelihood ratio (LR) and logistic regression model (LRM) to map landslides predicting and landslide sensitivities in the Three Gorges region based on LiDAR data, digital mapping camera (DMC) data and geological maps, and the accuracy of LRM has reached 88.8%.

5. Conclusion

5.1. Conclusion

Landslide predicting is a worldwide problem due to the complexity and variability of the gestation environment, formation mechanism and disaster factors of the slope body. This paper believes that the selection of landslide prediction index system and the construction of predicting model are the core issues of landslide predicting and forecasting. Reasonably selecting the key control factors of landslide to construct a dynamic predicting model under different characteristics of dynamic control factors is the key to achieve accurate landslide predicting.

(1) The technical means of landslide monitoring and forecasting over the years have experienced multi-source and multi-resolution data from field aerial surveys to high-resolution satellite imagery, radar imagery and field verification. The geological environment conditions and trigger factors that may be obtained by remote sensing methods, as well as the stages of slope deformation and damage and the characteristics of each stage have been basically determined, a set of basic and effective landslides predicting and forecasting method based on remote sensing technology survey and statistical analysis have been formed, and the practical landslide predicting model and empirical formula have been established. However, the theoretical significance of many landslide predicting models are not clear, the factors of models are too many, and the relationship between factors is unclear, and the material and terrain condition factors obtained from some remote sensing data are too rough due to the complex geological environment of landslide areas. Making full use of aerospace remote sensing, differential interference radar and other technical means to reasonably determine the key factors of landslides, and obtaining them quickly and accurately to establish a landslide predicting model with clear physical relationship and clear relationship between factors is the task of research of landslide remote sensing predicting and early warning.

(2) Accurate landslide predicting and forecasting is a worldwide difficult problem due to the complex landslide breeding environment, the diverse development types and the changeable influencing factors. There are many landslide predicting methods such as the three-stage theory of landslide creep damage method and the landslide displacement-time curve change trend prediction model at present. However, the three-stage theory of landslide creep damage method mainly depends on the analysis and empirical mode of geological phenomena under ideal conditions, and it focuses on the quantitative analysis using mathematical methods and ignores the actual motion mechanism characteristics of the landslide, so the accuracy of the predicting model is susceptible, which will produces a large error in the actual creep damage time of the landslide. The research based on the landslide displacement-time curve is a great progress in the study of landslide predicting and forecasting, because it does not effectively use the information and eliminate the influence of the interference information, it can only predict the approximate deformation trend in the temporary sliding stage and cannot respond to the system characteristics and dynamic characteristics of landslide, it is transitional periods from qualitative research to quantitative qualitative research. With the development of various new technical means, scholars have summarized the predicting model such as the nonlinear dynamic model, fractal model and artificial neural network model through the perspective of system theory and nonlinear science. Methods
have matured, but there are still shortcomings such as unclear input-output logic and failure to respond to landslide system characteristics and dynamic characteristics. The landslide system is constantly undergoing material and energy exchange with the outside world in fact, it is a complex system with nonlinear, random, mutated and multi-scale properties. The landslide predicting model is a quantitative, dynamic, updateable and continuously optimized prediction model for the complexity and non-deterministic requirements of system evolution.

(3) The geological environment information, measured information, historical hazard information and information in different spatial and spectral resolutions from different satellites, aircraft and ground platforms were fused to more effectively utilize these multi-source information for landslide predicting and forecasting. Scholars have done a lot of research on the basis theory of multi-source data fusion, which promoted the rapid formation of a variety of multi-source data fusion methods and their continuous development in the field of landslide sensitivity analysis, forecasting and forecasting. The main goal of multi-source data fusion is to achieve selective information optimization, while the scope and fusion effects of some data fusion methods is often limited due to they should meet certain preconditions of the method. Therefore, developing higher-level multi-source information fusion methods to improve accuracy and increase the use of spatial or structural information is the focus of current multi-source information fusion.

5.2. Dynamic predicting of loess landslide

It is very difficult to accurately predict and forecast landslide disaster due to the complexity, variability and randomness of breeding environment, development type and disaster-causing factors. A lot of researches have been carried out by scholars at home and abroad, but there are still some shortcomings such as the unclear relationship between input and output logic and the inability to respond to landslide system characteristics and dynamic characteristics. The landslide predicting model need to be a dynamic, updateable and continuously optimized prediction model for the requirements of complexity and non-deterministic of landslide system evolution. Therefore, in order to accurately predict landslides, it is necessary to consider the static factors and its characteristics that affect the development of landslides to understand the geological environment characteristics of landslide formation, and to consider the dynamic factors and characteristics that affect the occurrence and development of landslides to understand the effects of rainfall, soil moisture and other factors on the development of landslides. The traditional method has not been able to meet the requirements of landslides forecasting. Based on the summary of the formation mechanism of landslide hazards, we used GIS platform to comprehensively manage and analyze geological environment data, monitoring data, remote sensing image data and historical geological disaster data to study the change law of landslide body from static to dynamic. And the organic combination of qualitative predicting and quantitative forecasting techniques were used to predict and forecast the occurrence and development of loess landslides by dynamic modeling on the basis of above method. The technology roadmap is shown as Fig. 1.
Spatial and temporal scaling
Data fusion
Multi-source data system of landslide key controlling factors
Remote sensing information
Geological environment information
Field survey information
Historical hazard information
Interpretation/inversion/calculation/classification/layerization/spatial interpolation/Hydrus simulation/digitization
Landslide hazard basic information database (vector data/raster data/chart data)
Spatial and temporal scaling
Multi-source data system of landslide key controlling factors
Support vector machine analysis
Comprehensive prediction model of loess landslide
Sensitivity analysis of model factors
Uncertainty analysis/ROC analysis
Prediction model optimization/validity check

Fig. 1. The technology roadmap.

As we can see in the Fig.1, the dynamic predicting of landslide hazards must firstly establish and obtain the multivariate and multi-dimensional factors which coordinate with geographic coordinates and affect the occurrence and development of loess landslides based on the characteristics of loess landslides and regional geological environment under the guidance of landslide geology theory, and to establish a basic database of key factors. Research of up-scaling and data fusion on multi-dimensional key factors to obtain a data system which containing more features and details. The index layers of key factor affecting the occurrence of loess landslide that from the post-fusion information system were obtained as the index for constructing the predicting model. Finally, the factor sensitivity of the predicting model was analyzed to further optimized the predicting model, and the predicting model was verified using the field measured data and historical disaster data.

This paper systematically analyzed and summarized the research actuality on landslide predicting and forecasting, loess landslide predicting and forecasting, landslide remote sensing investigating and landslide predicting and forecasting based on multi-source data fusion at home and abroad. On this basis, a landslide dynamic predicting model based on multi-source information fusion and its specific technical route were proposed.

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