STUDY ON REMOTE INTELLIGENT MONITORING SYSTEM OF SLOPE BASED ON SARMA ALGORITHM AND ARCGIS

Jian Gong[1], Kexin Zhang[2], Houji Zhang[3] and Honglei Zhang[3]

1. *China Railway Fifth Survey and Design Institute Group Co. LTD, Design Department, Beijing, No.9 Kangzhuang Road, PR of China; 67543320@qq.com*
2. *Shenyang Jianzhu University, Department of Bridge Engineering, Shenyang, No.25 Hunnan Zhong Road, PR of China; jt_zkx@sjzu.edu.cn*
3. *Beijing Xinqiao Technology Development Co., Ltd, Bridges and Tunnels Department, Beijing, No.8 Xitucheng, PR of China; Hongleizhang_Xq@163.com, 765310906@qq.com*

ABSTRACT

This article is devoted to promote the remote intelligent monitoring system of slope research, reduce the threat of natural disaster to the highway. Firstly, a typical slope on Liu-An highway was selected as the research object. Then, based on the Sarma algorithm and considering the influence factors such as inhomogeneous boundary conditions, water content and reinforcement angle, a slope stability analysis system based on the improved Sarma algorithm is developed to build an engineering geological model and a remote intelligent monitoring system platform for the slope. On this basis, we selected the slope of typical road sections for remote monitoring and pre-warning. ArcGIS technology is used to carry out difference analysis of monitoring data, realize GIS 3D visualization, and verify the 3D visualization monitoring effect of the system. The results show that the system is stable and reliable. The range and precision meet the specification requirements and can effectively realize the 3D visualization monitoring of highway slope. It can also realize four-level pre-warning, which lays a foundation for the long-term safe operation of highway.

KEYWORDS

Highway slope, Sarma algorithm, ArcGIS, 3D visualization, Intelligent monitoring

INTRODUCTION

Since the reform and opening-up, China's highway construction has developed rapidly. By the end of 2019, China's total highway mileage was 5,012,500km, including 149,600km of expressway, 518,600km of trunk highway, and 4,200,500km of rural road. Nearly two thirds of China's land area is mountainous. A considerable part of highways intersperses in the mountains, forming a large number of complex high cutting slopes, which destroy the balance state of the original mountain slope. Natural disasters such as landslide, debris flow and water destruction have become the most serious natural disasters threatening highways, causing serious economic losses [1]. A series of social behaviours, such as mining, explosion and logging, further aggravate the occurrence of highway slope landslide [2].

At present, the United States, Canada, the Netherlands and other countries and regions have developed relatively mature in slope intelligent monitoring and landslide warning. Sensor research and development, geological model calculation, intelligent monitoring system design, disaster warning and long-distance signal transmission have all been widely applied [3-4]. In China, remote identification, monitoring and pre-warning of highway slopes are still in the stage of theoretical simulation and experimental research and development [5-9]. Slope monitoring methods mainly include deformation monitoring, stress monitoring, water monitoring, rock mass failure acoustic emission monitoring, etc., among which deformation monitoring is the most widely used. Slope monitoring equipment and technology mainly include sensor technology, 3S technology (GPS, GIS, RS), robot technology, time domain reflection technology, perception node network, Internet of things technology, etc.

There are limitations to using these techniques alone. The main reason is that the landslide has many conditions, such as deformation, moisture content, friction resistance in soil body, shear Angle, etc. The development of the remote intelligent slope monitoring system based on Sarma algorithm and ArcGIS technology can "monitor the essence" rather than just "monitor the phenomenon". According to the influencing factors of landslide, the monitoring of non-homogeneous boundary conditions, water content and reinforcement Angle is integrated into the system for analysis, and the calculation model is improved to make the analysis results more consistent with the reality.

MECHANICAL MODEL OF IMPROVED SARMA ALGORITHM

Based on the limit equilibrium theory and homogeneous boundary conditions, Sarma proposed an algorithm for stability analysis of slopes or other structures in 1979, called Sarma algorithm, without considering various drainage conditions and complex stress conditions [10]. He believed that the sliding body should overcome the shear strength of the main sliding surface and its own strength. The sliding body breaks into blocks that can slide relative to each other, and then slide as a whole, rather than forming an ideal sliding camber or plane.

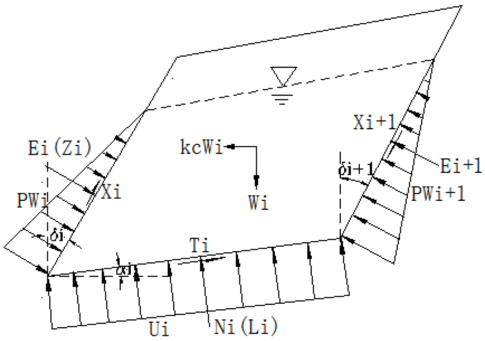

Fig. 1 - Mechanical model based on the Sarma algorithm

According to the mechanical model, when the slope reaches the ultimate equilibrium state under external loads such as earthquake, rain, snow, and vehicles, the equilibrium equation in Table 1 will be established.

Tab. 1 - Parameter list

Parameter	Equation	Number of blocks	Number of Equations
Resultant force along the X axis	$\sum F_x = 0$	N	N
Resultant force along the Y axis	$\sum F_y = 0$	N	N
Resultant moment	$\sum M = 0$	N	N
The bottom slip meets the Moor-Coulomb criterion	$T_i = f(N_i, CB_i, \varphi B_i)$	N	N
The sideslip meets the Moor-Coulomb criterion	$X_i = f(E_i, CS_i, \varphi S_i)$	N	N-1

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According to the above equilibrium equation, the formula for solving the stability coefficient (F_s) and critical horizontal seismic coefficient (kc) of the slope is derived and simplified, and the following recursive relation is obtained.

$$E_{i+1} = a_i - p_i \cdot kc + e_i \cdot E_i \tag{1}$$

In the Equation 1, kc is the critical horizontal acceleration coefficient of earthquake, E_i and E_{i+1} are the normal pressure acting on both sides of the i block(kN), a_i, p_i and e_i are constant coefficients, and their values are as follows:

$$a_i = \frac{W_i \cdot \sin(\phi B_i - \alpha_i) + R_i \cdot \cos\phi B_i + S_{i+1} \cdot \sin(\phi B_i - \alpha_i - \delta_{i+1}) - S_i \cdot \sin(\phi B_i - \alpha_i - \delta_i)}{\cos(\phi S_{i+1} - \alpha_i - \delta_{i+1} + \phi B_i) \cdot \sec\phi S_{i+1}} \tag{2}$$

$$p_i = \frac{W_i \cdot \cos(\phi B_i - \alpha_i)}{\cos(\phi S_{i+1} - \alpha_i - \delta_{i+1} + \phi B_i) \cdot \sec\phi S_{i+1}} \tag{3}$$

$$e_i = \frac{\cos(\phi S_i - \alpha_i - \delta_i + \phi B_i) \cdot \sec\phi S_i}{\cos(\phi S_{i+1} - \alpha_i - \delta_{i+1} + \phi B_i) \cdot \sec\phi S_{i+1}} \tag{4}$$

Sarma algorithm cannot be directly applied to the engineering practice, as it cannot solve the problems under the complex geological and hydrological background. Its deficiencies are mainly as follows:

(a) It is only applicable to slope stability calculation under homogeneous boundary condition.
(b) The drainage conditions of the slope are not considered.
(c) The condition of slope load and reinforcement are not considered.
(d) The slope stability calculation and analysis under the combination of multiple working conditions cannot be carried out.

Therefore, it is not enough to consider homogeneous boundary conditions only, but consider homogeneous boundary conditions at the same time. In practical engineering, the water content of soil and various load conditions are relatively complex, and some slopes are reinforced, which should be the parameters of slope stability analysis. Considering various working conditions, Chinese researchers have derived the iterative formula for solving the stability coefficient with slope surface forces, and modified the coefficient as follows [11].

$$a_i = \frac{W_i \cdot \sin(\phi B_i - \alpha_i) + R_i \cdot \cos\phi B_i + S_{i+1} \cdot \sin(\phi B_i - \alpha_i - \delta_{i+1}) - S_i \cdot \sin(\phi B_i - \alpha_i - \delta_i) + F_i \cos(\phi B_i - \gamma_i - \alpha_i)}{\cos(\phi S_{i+1} - \alpha_i - \delta_{i+1} + \phi B_i) \cdot \sec\phi S_{i+1}} \tag{5}$$

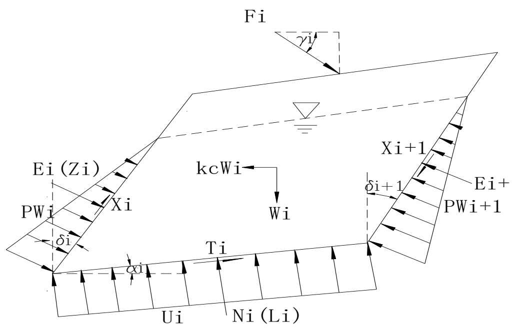

Fig. - 2 Mechanical model based on the improved Sarma algorithm

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REMOTE INTELLIGENT MONITORING SYSTEM OF SLOPE

The system composes four parts: data acquisition device, data transmission system, computer analysis and management system and remote monitoring system. It can realize real-time data acquisition and integrated processing, remote control and signal transmission, and four-level pre-warning. At the same time, it can carry out difference analysis of monitoring data based on ArcGIS technology and realize GIS 3D visualization display. The working principle is shown in Figure 3.

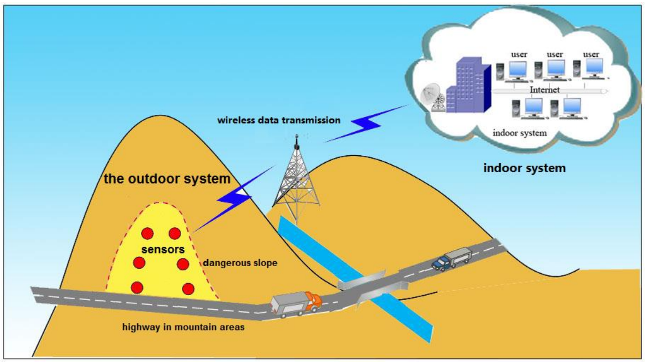


Fig. 3 - Operating principle diagram of the system

Sensor, data acquisition and transmission system

According to the project demand, the slope surface displacement, internal displacement, water pressure, rainfall is monitored. GPS, fixed inclinometer, pore water pressure gauge and SRY-2 high precision digital rain gauge was used for monitoring (Figure 4). In order to realize long-distance wireless transmission of data, a matching signal acquisition and transmission device is also set up (Figure 5). At the same time, in order to ensure the continuous operation of the system in the field, the system adopts solar power supply and is equipped with lightning protection device (Figure 6). The accurate information of the instrument is shown in Table 2 below.

Fig. 4 – Sensors

Fig. 5 - Signal transceiver device

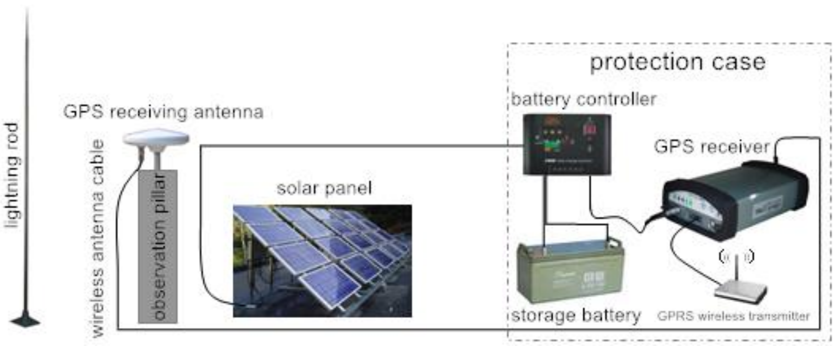


Fig. 6 - Schematic diagram of solar power supply

Tab. 2 - Engineering instrument characteristics

Instrument	Basic functionality	Accuracy of instrument	Methods Instrument Use
GPS	Monitor, query, and warn surrounding soil displacement	0.9m~2m	Traditional hand-held instruments or stand signal amplifiers
fixed inclinometer	It is used for long-term automatic measurement of horizontal displacement and dip Angle of deep foundation pit slope buildings, Bridges and ships	The measurement error of the top Angle is less than or equal to 1°, and the measurement error of the azimuth Angle is less than or equal to 2°	An instrument is drilled into the inner structure of the building to measure the inner tilt of the building structure
pore water pressure gauge	Measuring the pore water pressure inside the building can synchronously measure the temperature of the burial point	⩽0.08%FS	The drilling method is buried inside hydraulic buildings and other structures
SRY-2 high precision digital rain gauge	Used to measure temperature, humidity and temperature change within a fixed range	⩽±2%	Manual placement in advance, set up in a fixed position, regular inspection

Data receiving and analysis system

Data receiving and analysis system includes navigation chart, monitoring analysis, record display, user management, parameter setting and other modules.

It can realize the functions of monitoring point positioning, setting monitoring parameters, setting monitoring frequency, encryption management, data export, automatic mapping and GIS visualization analysis, etc. In order to realize the visual analysis function of GIS, it is necessary to make use of the GIS "Add XY Data" tool to count the 3D coordinate data of the monitoring points. Then, based on these data, stereo distribution graphs of monitoring points are automatically generated. Due to the sparse distribution of monitoring points, the existing 3D coordinates are relatively discrete, and the 3D effect of the slope cannot be realized, so its visualization effect is poor. Therefore, the method of spatial interpolation is adopted to compensate. By superposition analysis of spatial interpolation coordinate data and 3D coordinate data of monitoring points, a visual graph can be generated which is in line with the actual situation.

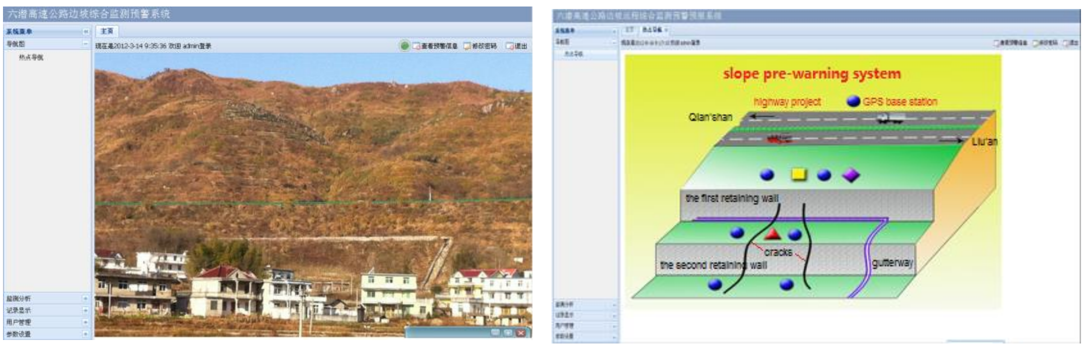


Fig. 7 – System operation interface

Fig. 8 - 3D visualization design sketch

Hierarchical pre-warning system

According to the monitoring precision and principle of slope surface displacement, GNSS instruments buried in the soil and measuring tubing in inclinometers, the four-level pre-warning mode is established. The slope is classified as red, orange, yellow and blue according to the danger degree, corresponding to states of landslide pre-warning, imminent landslide pre-warning, relatively stable pre-warning, stable pre-warning. The specific level and warning division are shown in Table 2.

Tab. 3 - Pre-warning grade and standard of displacement monitoring

<table>
<tr><th>Pre-warning level</th><th>States forecast</th><th>Rule 1： cumulative displacement(Z/(mm/m))</th><th colspan="3">Rule 2： displacement increment(ΔH/mm)</th></tr>
<tr><td>blue</td><td>stable</td><td>0~35</td><td>20-30 becomes yellowing</td><td rowspan="2">30-80 becomes orange</td><td rowspan="3">>80 becomes red</td></tr>
<tr><td>yellow</td><td>relatively stable</td><td>35~55</td><td></td></tr>
<tr><td>orange</td><td>imminent landslide</td><td>55~85</td><td></td><td></td></tr>
<tr><td>red</td><td>landslide</td><td>＞85</td><td></td><td></td><td></td></tr>
</table>

PROJECT CASE

The system has been applied in the slope monitoring highway project from Liu'an to Qian'shan. Remote real-time monitoring is carried out on the right-side slope of K125+550~K125+725. The maximum height of the slope is 35m, and the water network is developed. From top to bottom, the slope is filled with artificial soil, quaternary sandy soil, sub-clay and strongly weathered granite. The layout of monitoring areas and points is shown in Figure 9 and Figure 10.

Fig. 9 – Monitoring area

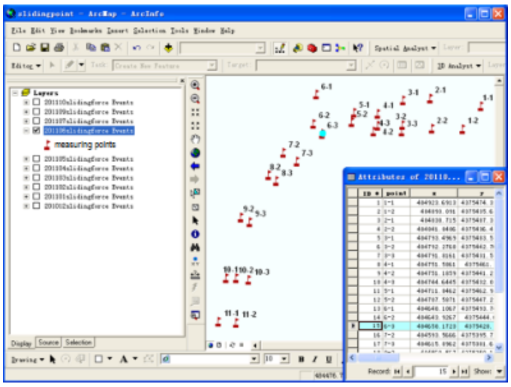
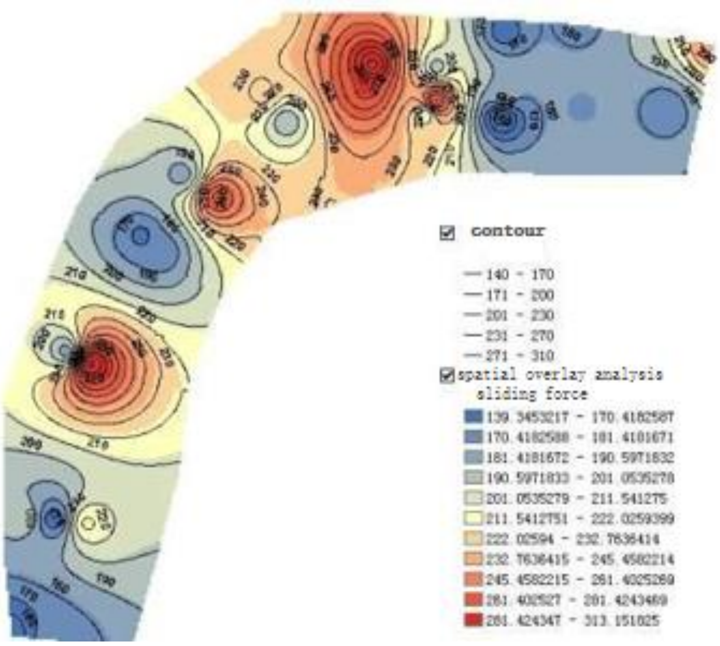


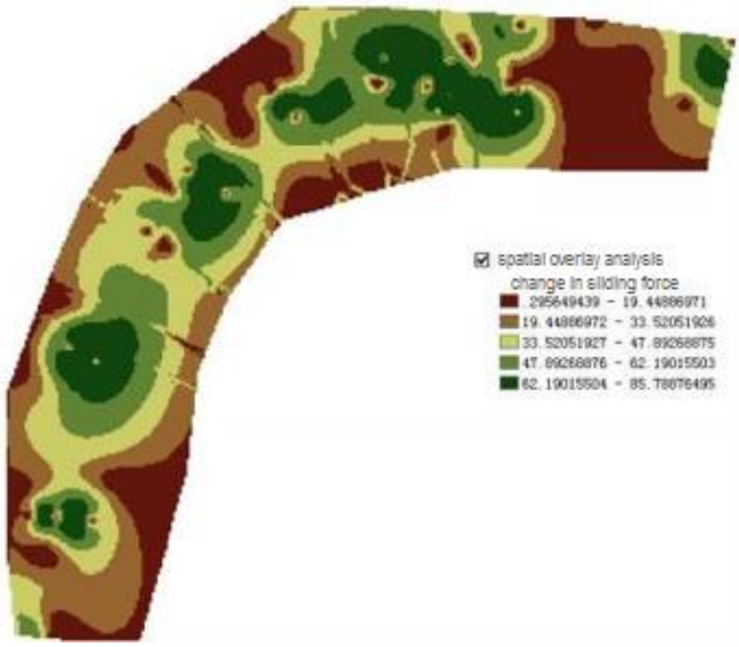
Fig. 10 - Layout of measuring points

The coverage area of the monitoring points is limited. Although the data of the surrounding areas can be obtained through spatial interpolation, with the increase of the distance, the accuracy of the data is reduced and the reference value is basically lost. Therefore, in this project, the effective influence area of comprehensive monitoring was determined and superimposed with the spatial interpolation analysis results of monitoring parameters (Figure 11). In the figure, the curve represents the contours of sliding force, and the colour represents the variation of sliding force (unit: kN).



(a)

Fig. 11 - Monitoring data stack and analysis diagram



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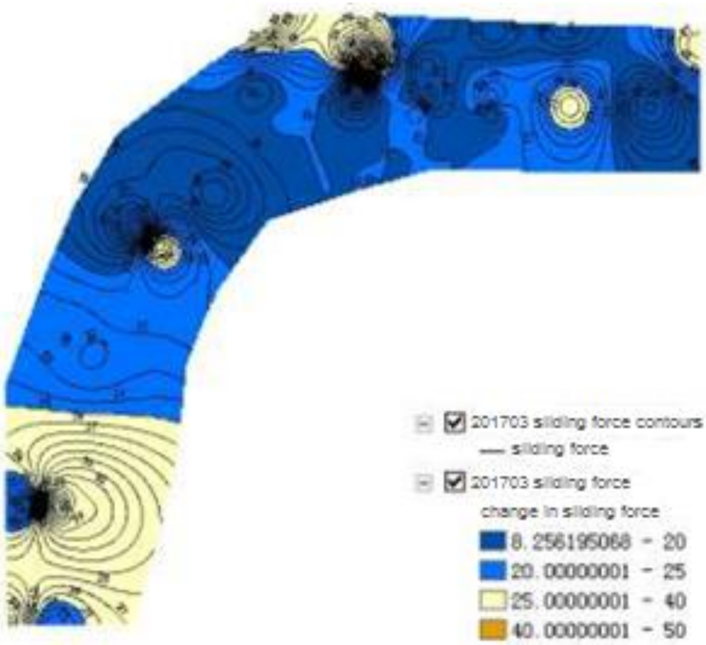
(b)

Fig. 11 - Monitoring data stack and analysis diagram

The final monitoring results are shown in Figure 12.

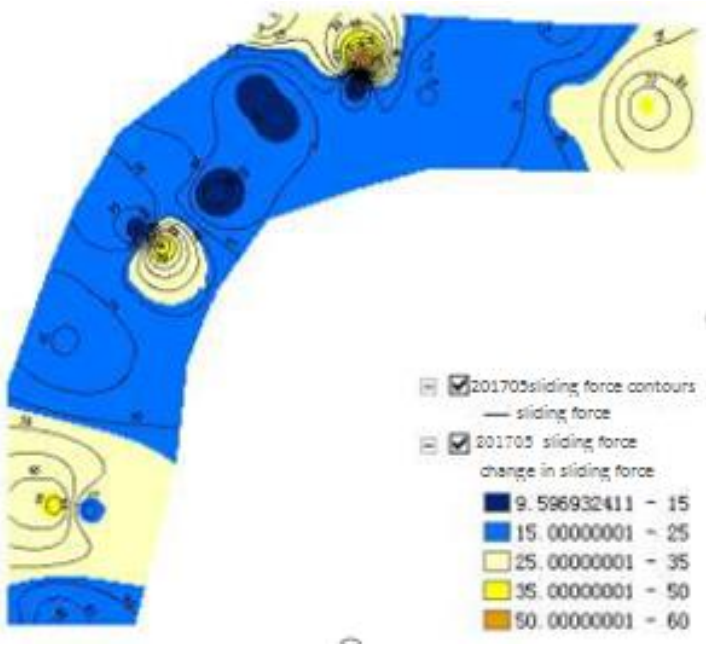
In this slope detection project from Lu'an to Qianshan, after real-time three-dimensional visual monitoring of slope stability of this project, the detection results are very intuitive, the slope deformation has been effectively controlled, and the safety performance has been greatly improved, so that the whole project is in a stable state.



(a) 2017.3

Fig. 11 - Monitoring data stack and analysis diagram

(b) 2017.4



(c) 2017.5

Fig. 12 - Results of monitoring

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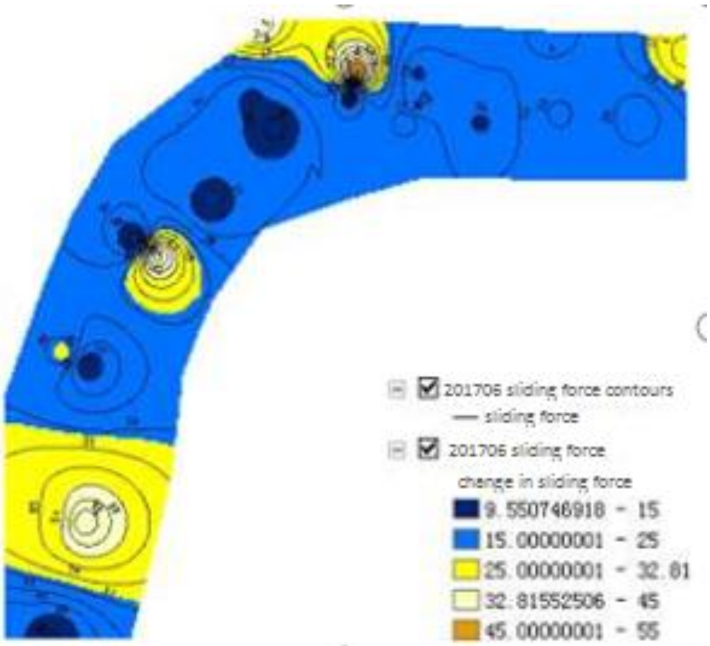
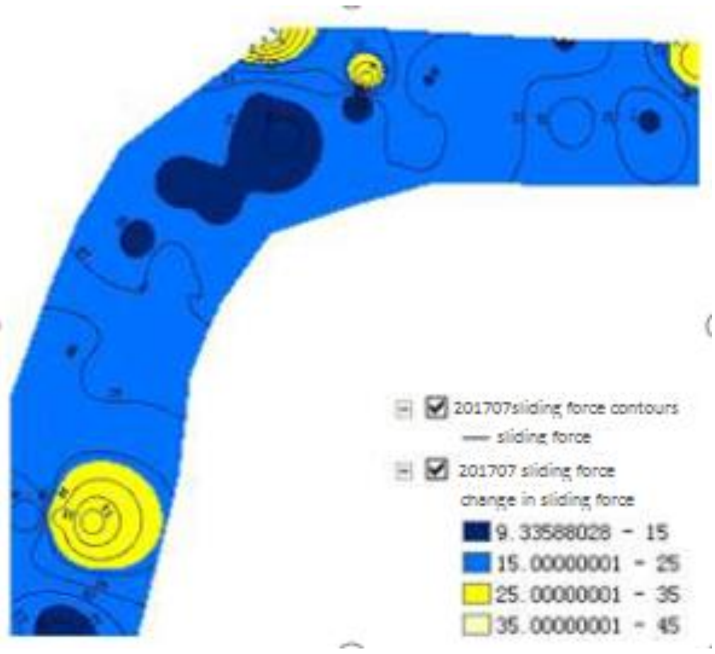
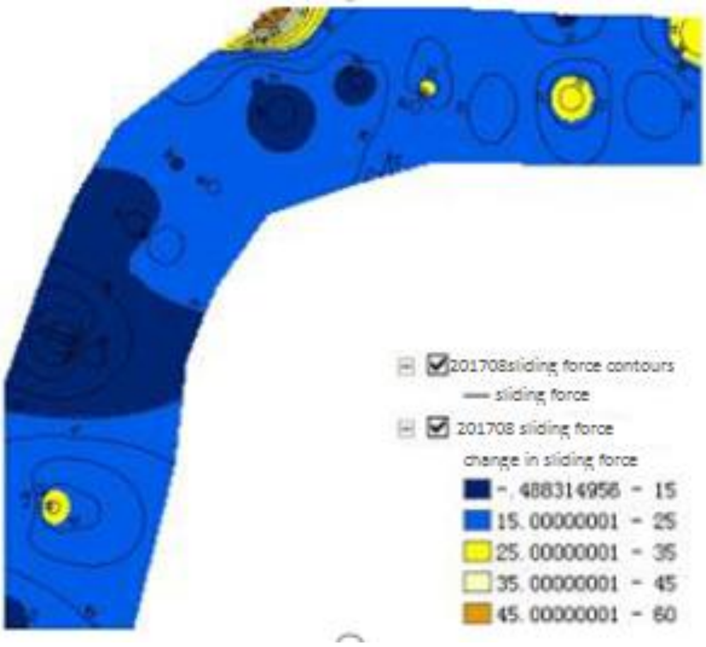


(d) 2017.6

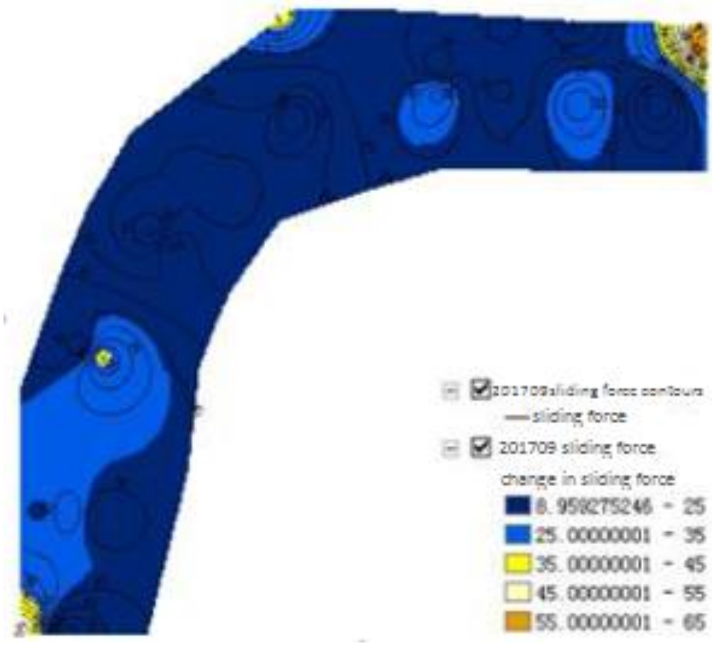


(e) 2017.7

Fig. 12 - Results of monitoring

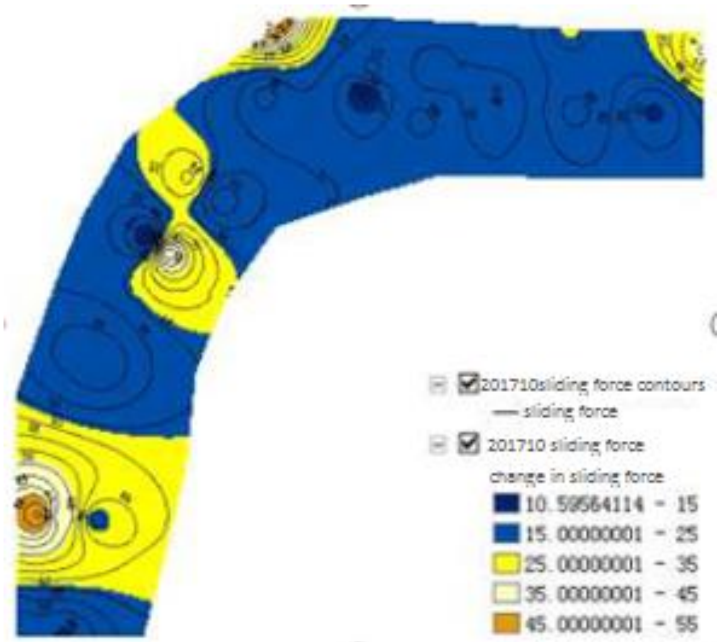


(f) 2017.8

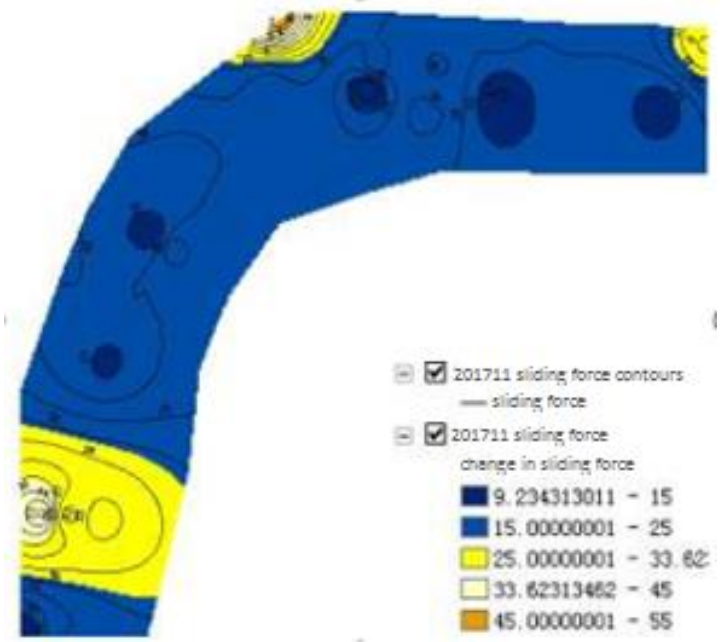


(g) 2017.9

Fig. 12 - Results of monitoring

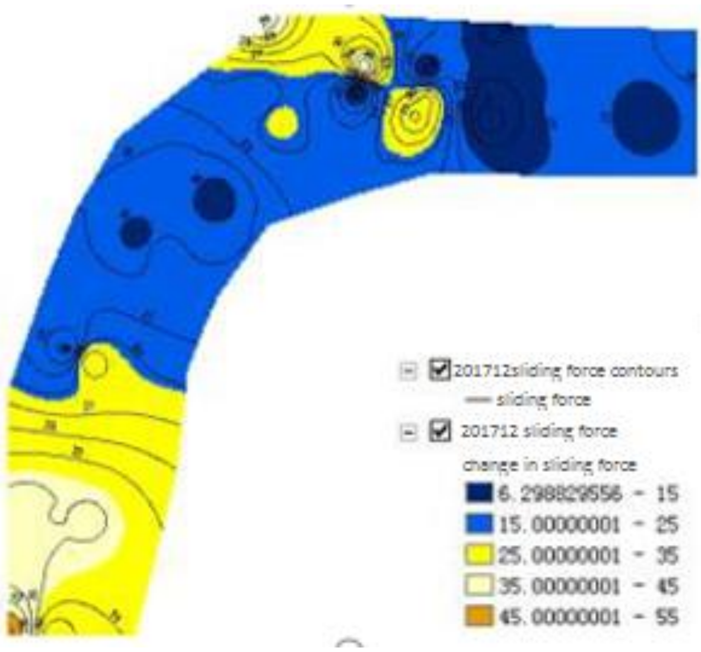


(h) 2017.10

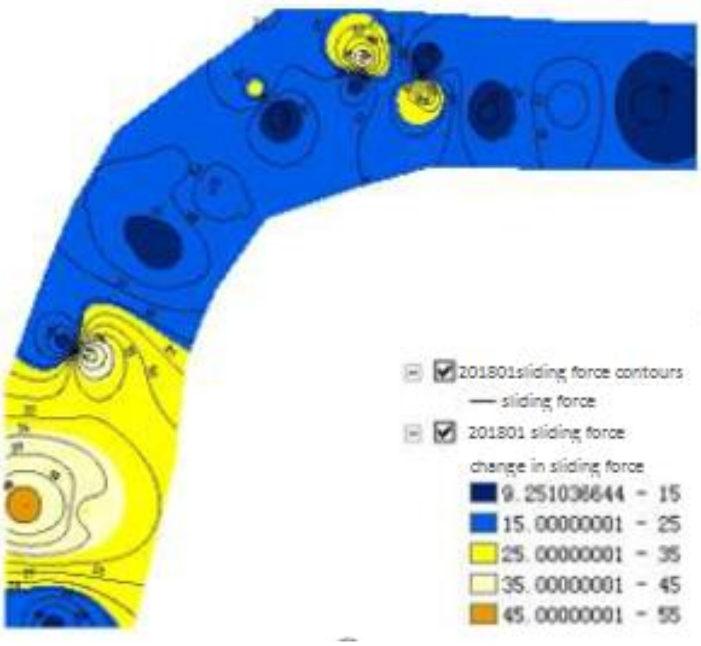


(i) 2017.11

Fig. 12 - Results of monitoring

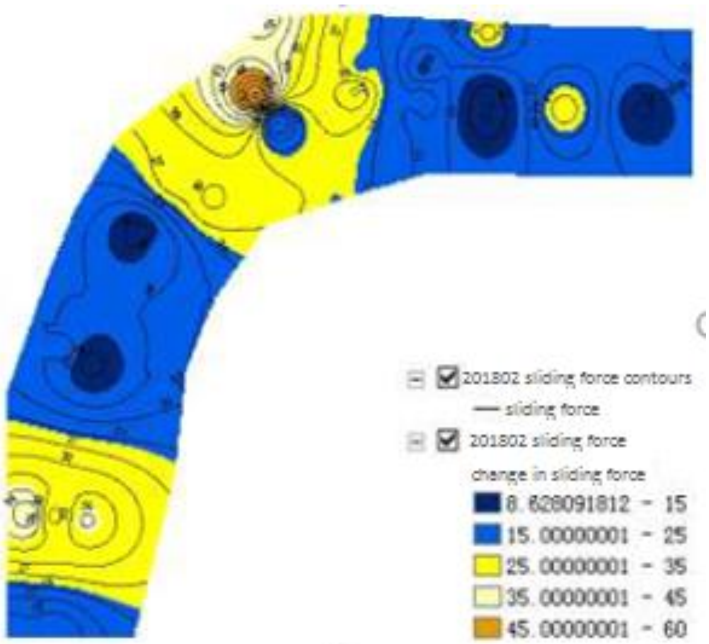


(j) 2017.12

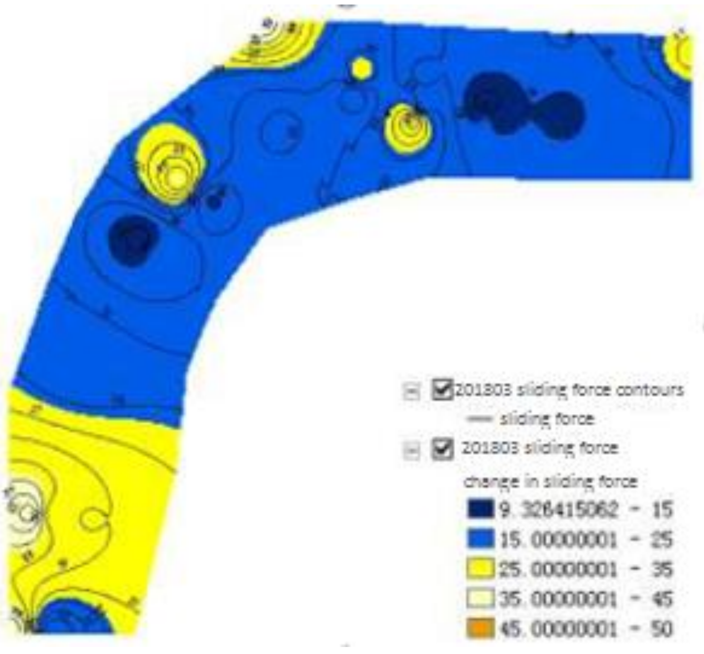


(k) 2018.1

Fig. 12 - Results of monitoring

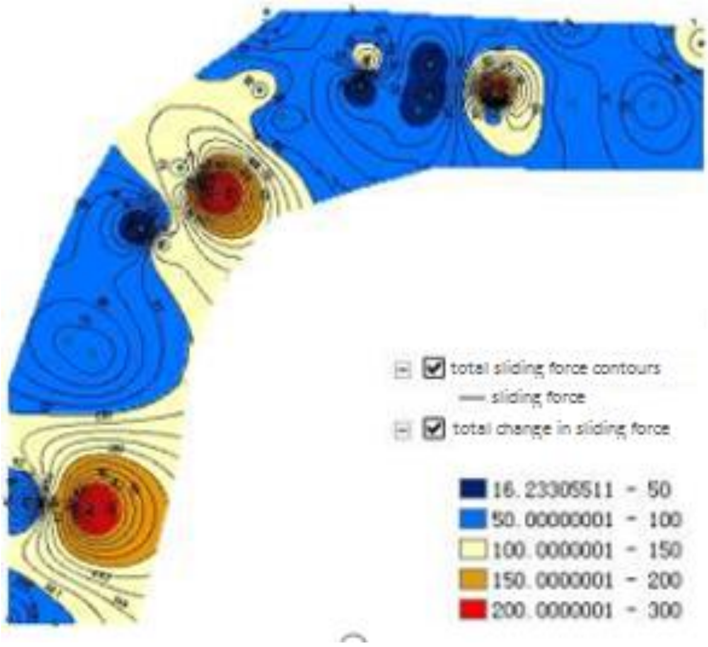


(l) 2018.2



(m) 2018.3

Fig. 12 - Results of monitoring



(n) cumulative displacement

Fig. 12 - Results of monitoring

Through the 3D visualization of slope stability research and analysis, the main conclusions can be drawn as follows:

(a) GIS 3D visualization analysis results confirm that the road slope remote intelligent monitoring system based on ArcGIS technology can carry out effective 3D visualization monitoring of the slope.

(b) After the implementation of monitoring, the deformation increment of the slope is not more than 5mm each month, and the slope is in a stable state.

(c) The 3D visualization of slope stability research and analysis can judge the stability of the slope by color, which is very intuitive. At the present stage, the slope of the project is basically blue, and a small part of it is yellow, which indicates that the current slope is stable and can guarantee the safe operation.

CONCLUSION

(a) The force in the rock mass of highway slope is complex, which is affected by many factors such as water content, reinforcement angle, inhomogeneous boundary conditions, etc. So it is necessary to modify the mechanics formula under ideal conditions to reflect the real stress state of slope sliding surface, so as to achieve accurate pre-warning.

(b) In this paper, the pre-warning level and standard of highway slope instability are put forward, and the evaluation method of quantitative pre-warning grade is taken displacement increment and cumulative displacement as indexes.

(c) The application and popularization of the system in the highway project from Lu'an to Qian'shan proves that the improved Sarma algorithm is suitable for engineering practice. GIS 3D visualization analysis technology can make slope monitoring results more intuitive and effective. Once landslide signs occur, the displacement and risk level of the monitoring point can be intuitively determined. Compared with the conventional methods, it is more convenient to help the managers to make decisions in time, and provides an effective means for the pre-warning and monitoring of highway slope landslide disaster, with remarkable economic and social benefits.

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