Research on methods of investigation and analysis of highway slope stability after flood based on InSAR and field investigation

Jianbo Fan¹, Xingbing Xiong ¹ and Xi Peng²*

¹Guizhou Expressway Group Co., Ltd., Guiyang, Guizhou 550004, China;
²Leshan Guanying New District Development and Construction Management Committee, Leshan, Sichuan 614800, China.
*Corresponding author: 201822000540@stu.swpu.edu.cn.

Abstract: The stability of highway slopes after floods is related to the smooth operation of traffic, construction and other related projects along the road. Taking highway slopes in Guizhou Province as the research object, conducting InSAR monitoring and on-site surveys on them, and obtaining a large amount of slope characteristic data after flood, the main conclusions are as follows: InSAR technology can study the influence of highway slope stability after flood, therefore, it saves a lot of manpower and time cost, uses on-site survey method to count the relevant characteristics of the slope along the highway, and uses the index system method to evaluate the risk level of the slope. It is believed that the road slope is prone to poor stability after the flood, and the risk level is higher.

1. Introduction
China's highway construction has developed rapidly [1]. By the end of 2018, the mileage of national and provincial trunk highway had reached 735,200 km, and the mileage of expressways had reached 633,300 km. A national trunk highway network has been basically established that "radiates from the capital to the provincial capital, connects multiple roads at the provincial level, connects prefecture-city expressways, and covers national roads at counties and counties". But what follows is a series of safety and stability issues in the process of expressway operation. China's highway maintenance mileage accounts for 98.2% of the total mileage, ranking among the highest in the world. The main reason for this phenomenon is that China has a large land area and complex regional geology and topography structure. Especially in the central and western regions of China, due to the existence of a large number of mountain and hill region and abundant rainfall, the highway slope is prone to after flood deformation and failure caused by heavy rain in summer and continuous rain in autumn [2], which seriously threatens the safety of transportation, construction and water conservancy projects along the road. Therefore, it is very important to investigate and analyze the after flood stability of the slope during the operation period, which is related to the prevention and control of slope deformation and failure.

At present, the analysis of slope deformation and failure after flood is mainly based on in-situ monitoring method, which has achieved some fruitful results. Damiano et al. [3] investigated the hydrological response of the volcanic slope based on the field monitoring method, and established an analysis and prediction model for slope failure caused by rainfall; Zhan Liangtong et al. [4] conducted
simulated rainfall and field monitoring based on the in-situ slope, proving that rainfall would reduce the shear strength of soil and local failure would occur to the weak soil along the structural plane; Kong Lingwei et al. [5] used weather stations and other equipment to carry out field tests on expansive soil slopes under atmospheric action, and they believed that rainfall is the key factor leading to the failure of expansive soil; Li Huanqiang et al. [6] carried out artificial rainfall test on the slope model based on optical fiber equipment and studied the slope deformation law. In recent years, with the continuous development of satellite remote sensing technology, some scholars also use relevant technology to analyze and study slope deformation and failure. For example, Deng Hui et al. [7] established a geological disaster image analytical model based on high-precision satellite, and analyzed the causes and development status of typical landslides; Ren Kaiyu et al. [8] carried out landslide instability prediction analysis on slope monitoring data based on remote sensing technology. Existing studies have obtained a large number of valuable conclusions from the two aspects: slope failure mechanism caused by rainfall and slope monitoring technology. But at present, there is a lack of research on monitoring slope deformation and failure phenomenon and stability analysis method after flood, and the relevant engineering experience is lacking.

Based on the technology of Synthetic Aperture Radar Interferometry (InSAR) and a large number of data from field investigation, this paper takes the typical highway sections of Guizhou Province as the research object. The key slopes of relevant sections are analyzed and discussed by using the after flood stability investigation and analysis method. The valuable engineering investigation conclusion is obtained, which has important engineering reference value for the operation and maintenance of highway slope.

2. Engineering situations

Guizhou Province is located in the southwest mountainous area with complex geomorphic and geological conditions. With the passage of the expressway operation time, part of the existing slope protection structures appear aging. In this paper, part of the operating expressways in Guizhou Province were investigated and studied. The Engineering survey objects are shown in Table 1.

| Route number | Route name (starting and ending stake number) | Mileage (kilometer) | Number of INSAR points (section) | Number of field investigation points (section) |
|--------------|---------------------------------------------|--------------------|----------------------------------|--------------------------------------------|
| G60          | Hukun Expressway (Kaima Section) (K1670+000~K1721+862) | 52                 | 39                               | 109                                        |
| G60          | Hukun Expressway (Sankai Section) (K1607+200~K1670+000) | 63                 | 9                                | 138                                        |
| G76          | Xiarong Expressway (Shuige Section) (K1124+000~K1235+000) | 111               | 10                               | 232                                        |
| S62          | Yuce Expressway (Yukai Section) (K3+000~K88+000) | 85                 | 5                                | 113                                        |
| S62          | Yuan Expressway (Kaityang Section) (K88+000~K145+000) | 57                 | 12                               | 69                                         |
| S15          | Songcong Expressway (Lihao Section) (K0+000~K50+000) | 50                 | 3                                | 128                                        |
| S84          | Tianhuang Expressway (Shihuang Section) (K14+000~K139+000) | 25                 | /                               | 20                                         |
| A total of   |                                             | 443               | 78                               | 809                                        |

The project area is located in the transition zone from Yunnan-Guizhou Plateau to Hunan-Guangxi Hilly Basin. According to the formation rock and the geological exogenic force, the territory can be divided into karst landform area, denudation and erosion landform area. The northwestern part of Zhenyuan-Kaili line belongs to the karst landform area, and the common landform forms include peak cluster, peak forest, stone forest, karst cave, dissolved depression, natural bridge, and subsurface stream. The northwestern part of Zhenyuan-Kaili line belongs to the karst landform area, and the common landform forms include peak cluster, peak forest, stone forest, karst cave, and subsurface stream. The southeastern part of the Zhenyuan-Kaili line belongs to the denudation and erosion landform area, which is mainly composed of clastic rocks. The mountain is large and deeply cut, and often forms ridge-shaped mountains. It belongs to the mid-subtropical monsoon humid climate zone, with an annual average temperature of 14°C ~ 18°C, rainfall of 1000 ~ 1500 mm, and
relative humidity of 78 ~ 84%. There are more than 2,900 rivers in the project area, with Qingshuijiang River, Wuyang River and Duliujiang River as main cuttings, spreading in the shape of branches. In the surface water, Qingshui River and Yanghe River to the north of Miaoling belong to the Yangtze River system, while Duliujiang River to the south of Miaoling belongs to the Pearl River system. The rivers and trenches in the field region are more developed, and most of them are distributed in the shape of branches, with deep cuts, and the flow of torrential valley varies greatly. The lithology of the project is complex, which is composed of quaternary, lower tertiary and triassic from old to new. The surface is mostly red clay, clay, gravel soil and silty clay, etc., which are distributed in the area.

3. Application method for stability of highway slope after flood

According to the actual situation of the project, the highway slope of the project is numerous and the geological structure is complex, so this paper uses the stability analysis method based on InSAR technology and engineering field investigation to save time, cost and human resources.

3.1. InSAR technology

InSAR is an emerging monitoring and control technology based on satellite interferometric synthetic aperture radar in recent years [9]. The main principle is that the synthetic aperture radar (SAR) sends microwave signals to the ground, scattered waves back to the radar information, and the received signals are recorded and processed to calculate and reflect the surface properties (water content, roughness, land cover types, etc.) and phase information (the distance between the sensor and the target object).

There are three main methods of InSAR data processing: D-InSAR, PS-InSAR and SBAS-InSAR. Among them, D-InSAR is affected by orbit error, atmospheric water, terrain error, etc., and the monitoring accuracy is at the centimeter level, which is difficult to meet the requirements of highway slope inspection [10]. SBAB-InSAR requires fewer SAR images than PS-InSAR, generally more than ten scenes, and is suitable for large range of suburbs, mountainous areas and other areas with few relevant points [11]. Therefore, the SBAS-InSAR method was selected in this paper, and the monitoring data of radarsat-2, a Canadian commercial charging satellite, was used as the signal source. The band used was C-band, the resolution was 5m×5m, and the width was 125km*125km.

3.2. Field investigation

InSAR technology can save a lot of time and labor, but it also has obvious disadvantages. That is, due to the characteristics of satellite data and terrain changes caused by monitoring blind area, so it is necessary to use field investigation and evaluation as a supplementary means of InSAR monitoring. In this paper, InSAR monitoring technology is used to extract the historical deformation information of 443 km in all high-speed areas under the jurisdiction of Kaili Operation Center in a full range. The deformation information of the expressway and its vicinity is analyzed and compared, and the potential danger area is divided according to the size of the deformation quantity, which is regarded as the key object for investigation.

| Route name (starting and ending stake number) | Rock slope (section) | Soil slope (section) | Soil-rock composite slope (section) | Fill side slope (section) |
|---------------------------------------------|----------------------|---------------------|------------------------------------|-------------------------|
| Hukun Expressway (Kaima Section) (K1670+000~K1721+862) | 87 / | / | 15 | 7 |
| Hukun Expressway (Sankai Section) (K1607+200~K1670+000) | 134 / | / | 2 | 2 |
| Xiarong Expressway (Shuige Section) (K1124+000~K1235+000) | 205 | 11 | 4 | 12 |
| Yuce Expressway (Yukai Section) (K3+000~K88+000) | 102 | 4 | 3 | 4 |
4. Application method for stability of highway slope after flood

4.1. The result of InSAR monitoring

According to the results of InSAR monitoring and calculation, and the deformation area is imported into the Örvay interactive map, the terrain and landform can be initially observed and judged. The preliminary observation and judgment can be made on the terrain and landform, so as to conduct field investigation and verification. Due to the large amount of identification data, in order to save space, this paper only takes G76 Xiarong Expressway (Shuige Section) as an example for introduction. The geographical locations of the monitoring points and highways are shown in Figure 1, among which G76-SG-05 are the numbers of the monitoring points. The monitoring data of InSAR are shown in Table 3, which indicates that the geographical and topographic relationship between the highway slope and the actual road can be accurately observed by using InSAR technology, which can significantly reduce the labor and time costs.

| Expressway (Section) | Number of Points | Number of Observations | Number of Times | Number of Days |
|----------------------|------------------|------------------------|-----------------|---------------|
| Yuan Expressway (Kaiyang Section) (K88+000~K145+000) | 58 | 6 | / | 5 |
| Songcong Expressway (Liluo Section) (K0+000~K50+000) | 101 | 7 | / | 20 |
| Tianhuang Expressway (Shihuang Section) (K114+000~K139+000) | 20 | / | / | / |
| A total of (section) | 707 | 25 | 24 | 50 |

(a) Overview of monitoring point G76-SG-05
4.2. Field inspection results

The maximum deformation rate of G76-SG-08 monitoring point at XiaRong expressway (Shuige Section) monitored by InSAR was 2 cm/year. The field investigation at this point shows that the upward slope foot of K1199+910-K1200+190 section bulges and shearing out, the roadside ditch extrudes, the ditch cover breaks off, the road shoulder humps and is seriously deformed, the window-type protective wall and anti-slide pile deforms and cracks, the first and third slope bulges,
the framework anchor cable and lattice beam breaks and deforms, the anchor rope and anchor head is damaged, and the steel strand is exposed. The foot of the downward slope was slightly humps, the protective wall between piles cracked, and the frame anchor ropes on the third and fourth slope were cracked and deformed, as shown in Figure 2. Thus, it can be seen that using InSAR technology to analyze the deformation at the monitoring points is consistent with the field investigation results, which can significantly save labor and time costs.

5. Stability evaluation of highway slope after flood
Slope stability analysis methods are mainly divided into qualitative analysis [12] and quantitative analysis [13, 14]. At first, this paper uses qualitative analysis method, find out the main factors influencing the slope stability, the possible way of deformation and destruction and the mechanics mechanism of the slope unstability. The origin and evolution history of the geological body of the deformed slope are investigated. Thus, a qualitative description and explanation of the stability of the slope to be evaluated and its possible development trend are given. Also taking Xiarong Expressway (Shuige Section) site as an example, the investigation results are shown in Table 4. As shown in Table 4, the combination degree of slope structural plane is poor after flood, and the number of structural plane groups is obvious. This should be because the strength of rock and soil material decreases obviously after the water content of slope increases in flood season, which may lead to the deterioration of its stability.

| Number | Position | Type | Height (m) | Slope Angle (°) | lithology | Hardness | The number of structural plane development groups | Bonding degree of structural plane | Slope aspect (°) | Occurrence | Direction of Extroversion Structure |
|--------|----------|------|------------|----------------|-----------|----------|-----------------------------------------------|---------------------------------|----------------|------------|-----------------------------------|

Table 4. G76 Xiarong Expressway (Shuige Section) Field Investigation Results.
The slope risk index can be analyzed with the index system method by referring to the Code for Design of Highway Landslide Prevention (JTG-T 3334-2018) [15] and combining Table 3 and Table 4. The index evaluation system used in this paper is based on the expert consultation comprehensive evaluation scoring method, and the scoring value is 0~100. Firstly, the slope hazard index $S_H$ and slope hazard degree $S_{Hd}$ are calculated. According to the score value of each evaluation index $A$~$G$ and the corresponding weight coefficient. Among them, geometric features of section ($A$) (slope height and slope gradient), slope structure ($B$), hydrogeological conditions ($C$), regional geological conditions ($D$), slope deformation history ($E$), slope deformation status ($F$) and slope protection engineering status ($G$), as shown in Equations (1) and (2):

$$S_H = A \times \gamma_1 + B \times \gamma_2 + C \times \gamma_3 + D \times \gamma_4 + E \times \gamma_5 + F \times \gamma_5 + G \times \gamma_7$$ (1)

$$S_{Hd} = S_H / 100$$ (2)

Secondly, slope hazard index $S_V$ and slope hazard degree $S_{Vd}$ are calculated. The evaluation indexes include highway grade ($O$), surrounding facilities of highway slope ($P$), and the hazard degree of slope hazard to highway ($Q$), as shown in Equations (3) and (4):

$$S_V = O \times \gamma_8 + P \times \gamma_9 + Q \times \gamma_{10}$$ (3)

$$S_{Vd} = S_V / 100$$ (4)

Lastly, slope risk index $SRI$ can be calculated by using slope hazard risk $S_{Hd}$ and slope hazard risk $S_{Vd}$, as shown in Equation (5):

$$SRI = S_{Hd} \times S_{Vd}$$ (5)

After the slope risk index $SRI$ is calculated, the risks of each slope can be classified according to the Technical Specification for Risk Assessment of Highway Slope Engineering in Service (T/CECSG: E70-01-2019) [16], and the specific methods are shown in Table 5. Therefore, based on the analysis of InSAR monitoring data, through field detailed investigation, key review, calculation analysis, expert review and other analysis and research work, the stability analysis and evaluation and risk grade classification of the expressway slope can be carried out one by one. The stability evaluation method refers to "Code for Design of Highway Landslide Prevention" (JTG-T 3334-2018) [15], and finally different treatment measures are taken for slopes with different risk levels. Due to the limitation of space, G76 Xiarong Expressway (Shuige section) is still taken as an example. The result of risk assessment index are shown in Table 6. According to the comprehensive analysis, most of the risk grade of the slope along the highway after flood is higher than level one, which indicates that the rainfall in flood season has a significant impact on the stability of the slope. Some sections (G76-SG-008) suffered damage to retaining wall and slope structure, and the risk level was high. The results are consistent with the InSAR monitoring results and the field investigation results, indicating that the combined use of relevant methods to investigate and analyze the stability of highway slope after flood is very effective, and can effectively and quickly conduct large-scale slope risk monitoring.
Table 5. Slope risk classification.

| Risk level | Risk index          | Acceptance criteria   | Required engineering measures                                      |
|------------|---------------------|-----------------------|-------------------------------------------------------------------|
| Level one  | SR≥0.30             | Can be ignored        | Adopt daily maintenance management measures                       |
| Level two  | 0.30<SR≤0.40        | Permissible           | Strengthen maintenance management and increase slope monitoring measures if necessary |
| Level three| 0.40<SR≤0.55        | Basically acceptable  | Increase monitoring measures and strengthen control               |
| Level four | 0.55<SR≤0.65        | Basically unacceptable| Carry out risk warning, make emergency plan, and carry out special slope engineering investigation |
| Level five | SR>0.65             | Unacceptable          | Initiate emergency plan, carry out emergency rescue, arrange special treatment |

Table 6. G76 Xiarong Expressway (Shuige Section) Risk Assessment Results and Engineering Measures.

| Number     | Risk index | Stable condition | Risk level | Practical treatment measures                                      |
|------------|------------|------------------|------------|-------------------------------------------------------------------|
| G76-SG-005 | 0.32       | Stable            | Level two  | Strengthen Inspection and Control                                 |
| G76-SG-006 | 0.28       | Stable            | Level one  | Normal maintenance                                                |
| G76-SG-007 | 0.54       | Basically stable  | Level three| Close the cracks in the retaining wall and strengthen the observation of the deformation of the wall |
| G76-SG-008 | 0.60       | Unstable          | Level four | Add professional deep displacement monitoring measures, carry out treatment design according to the monitoring results, strengthen the observation of crack deformation at all levels of platform and slope surface and repair drainage ditch before carrying out the work |
| G76-SG-009 | 0.48       | Basically stable  | Level three| Strengthen crack deformation observation of retaining wall. If the deformation of roadbed and retaining wall is aggravated, adopt anchor rope to support |
| G76-SG-010 | 0.58       | Basically stable  | Level four | Add professional deep displacement monitoring measures, carry out treatment design according to the monitoring results, strengthen the observation of crack deformation at all levels of platform and slope surface |
| G76-SG-011 | 0.65       | Basically stable  | Level four | Add professional deep displacement monitoring measures, carry out treatment design according to the monitoring results, strengthen the observation of crack deformation at all levels of platform and slope surface |

6. Conclusion

Based on the satellite monitoring data and field investigation data, this paper studied the stability investigation and analysis method of typical expressway slope after flood, and the main conclusions are as follows:

1. SABS-InSAR technology can be used to study the influence range of highway slope stability after flood. InSAR monitoring data can greatly reflect whether the deformation of slope after flood season affects the normal operation of highway.

2. The structural plane instability of highway slope is easy to appear after flood. However, InSAR data is difficult to monitor slope structural plane, so InSAR technology also has obvious disadvantages. It is necessary to use field investigation for supplementary analysis, and the results of the two are highly correlated, which can save a lot of labor and time costs.

3. On the basis of the index system method based on the comprehensive evaluation of expert consultation and referring to the relevant norms, the risk assessment can be carried out according to the characteristics of the slope and the relevant geographical and geological conditions, so as to carry out the relevant monitoring and conservation measures.

4. The poor stability of highway slope tends to occur after flood, which is reflected in the development of structural plane and the combination degree of structural plane, which may be related to the nature of rock and soil, which needs to be further studied. In addition, the stability of a large number of highway slopes is poor after flood, and the risk level is high, which indicates that the engineering maintenance of highway during the operation period is still a long way to go.
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