ISSN 2706-655X Vol.3, Issue 7: 44-49, DOI: 10.25236/IJFET.2021.030708

Study on Finite Element Numerical Simulation of Rock Slope Based on Ground Penetrating Radar Detection

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Abstract: *Weathering degree of natural slope and its mechanical parameters have significant spatio-temporal variability. At present, the method of determining the mechanical parameters according to the suggestions of the specification ignores this phenomenon. In order to improve the accuracy of finite element numerical simulation results, a method for obtaining rock mass mechanical parameters based on ground penetrating radar (GPR) detection was proposed. Based on a rock slope of Xianyang international airport in Shaanxi province, the degree of fracture and water-rich inside the slope were detected by GPR, and the slope was divided into several units with different levels. Then, the mechanical parameters such as elastic modulus, Poisson's ratio and cohesion force of different units were obtained according to the specification. Fatherly, the finite element numerical simulation software MIDAS-GTS was used to establish the grid model of the slope, and the recommended values provided by the specification were used to calculate the sliding displacement of the slope. Compared with the field displacement monitoring data, the results showed that the numerical simulation values were closer to the monitoring values, indicating that the mechanical parameters obtained by this method were more consistent with the actual value of the rock mass.*

Keywords: *Slope engineering, Mechanical parameters, Finite element simulation, Ground penetrating radar, Detection*

1. Introduction

Affected by construction disturbance and rainfall scouring, the slope is prone to instability and decline, which affects the construction progress and even endangers the construction safety. Therefore, the prediction and evaluation of slope stability has become an important part of slope protection design and construction. At present, the common prediction and evaluation methods include theoretical estimation, soil model test, and numerical simulation analysis and field monitoring. In engineering practice, two or more methods are usually used for prediction and mutual verification at the same time. For example, the field monitoring is often used in conjunction with the numerical simulation analysis [1], [2].

Numerical simulation analysis is advanced, fast and convenient, which is suitable for various engineering projects and has been widely recognized and applied. In numerical simulation analysis, it is necessary to accurately grasp the mechanical parameters of rock mass, which is the key step to ensure the accuracy of simulation analysis results. At present, it is common to assign parameters according to the specification, which has good timeliness and convenience. However, the natural rock mass is a complex three-phase component, and its water-rich degree and fragmentation degree are uneven in three-dimensional space. The properties of surface and deep layer are different, and the larger the slope scale is, the more obvious the difference is. Under this condition, it is generally difficult to classify rock mass and assign mechanical parameters [3], [4]. Thus, it is difficult to ensure the validity of the calculation results and provide effective guidance information for engineering practice even if the classification and mechanical parameters assignment are carried out blindly.

Therefore, based on a rock slope of Xianyang international airport, this study proposes a method of using the GPR detection technology to divide the whole slope into different units. On this basis, MIDAS-GTS finite element numerical simulation software is used to analyze the stability of the slope, so as to provide relevant reference for numerical simulation of rock slope.

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2. Project Introduction and Study Scheme

2.1. Project Introduction

It was a rock cutting slope formed by manual excavation. It could be seen in the field that the slope was steep with an angle of 40 °and the overall water abundance and fragmentation were uneven, which was prone to slip failure. There were no buildings on the top of the slope, but the vegetation was developed. The slope was mainly composed of moderately weathered mudstone and calcareous mudstone. The site verification showed that the surrounding environment of the slope was simple, and there were no other facilities affecting the project. The length of the slope along the route was 32 m, and two steps were adopted in the longitudinal direction. The total height from top to bottom was 12.7 m, and the height of step 1 was 8.5 m. The left side of the slope was dominated by moderate weathering, and the rock mass was relatively complete without obvious joints and cracks. The middle-right side of the slope was strongly weathered with loose gravels. It could be seen that the overall integrity of the slope was general and the stability was poor. Finally, the anchor cable frame beam was used to reinforce it and the construction was completed in October 2020.

During April 10-19, 2021, continuous rainfall occurred in Xianyang area, resulting in high air humidity and wet surface. According to the report of the airport management office, the right side of the upper step, the middle part and the right side of the lower step collapsed on April 21st, which caused the frame beam damaged and the anchor cable exposed. The site investigation found that the soil in the middle and right part of the slope was wet, indicating that the water content was high. Fortunately, the rock mass on the left side was wet, but there was no obvious slip and the rock mass was relatively complete. Therefore, it is an important task to predict and evaluate the stability of the whole slope as soon as possible, so as to provide relevant reference for the subsequent countermeasures.

2.2. Study Scheme

The integrity and weathering degree of the slope were significantly uneven, and the water content was also quite different. It was unreasonable to regard it as V-grade or IV-grade rock mass. Therefore, abandoning the previous practice of grading and classification of the whole slope, the slope was divided into several units and then the grading and mechanical parameters assignments were carried out respectively, as the geological sketch was carried out and the GPR was used to detect the water abundance and fragmentation firstly, and then the slope was divided into units. Secondly, the elastic modulus, Poisson’s ratio and other parameters of each unit were initially assigned according to the suggestion of rock classification standard (GB/T50218-2014, China).

Therefore, based on the above rock block division and initial assignment of mechanical parameters, the finite element numerical simulation was applied to analyze the stability of the slope. Finally, the field monitoring measurement was used to verify the simulation results. Figure 1 shows the study scheme.

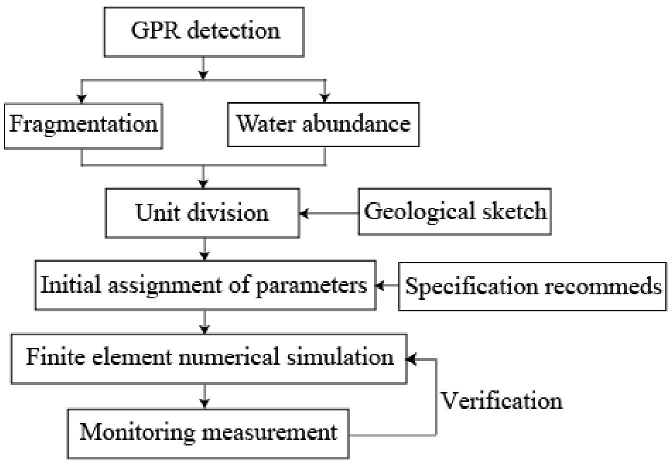

Figure 1: Study scheme

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3. GPR Detection

3.1. Detection Principle

GPR belongs to electromagnetic exploration technology, which has the advantages of good timeliness, simple equipment and convenient operation. In recent years, it has been widely recognized and applied in the field of geotechnical engineering. Compared with TSP (tunnel seismic wave predication method), GPR is a short-range detection technology, and its effective detection depth can reach 30-35 m depending on the ground conditions. GPR system consists of control computer, connecting cable and electromagnetic wave transmitting antenna. During the detection, the transmitting antenna will transmit the electromagnetic wave with a certain central frequency, velocity, phase and amplitude to the stratum according to the setting parameters of the control host.

According to the basic propagation theory of electromagnetic wave, it is a dielectric-free wave, which is essentially a unified field formed by alternating electric-magnetic fields [5], [6]. The natural soil is composed of solid, liquid and gas, which is both conductive and insulator in natural state. Obviously, the three-phase components in the soil belong to different dielectrics, so the contact surfaces of different components belong to the mutation band of electrical properties. When the incident electromagnetic wave penetrates the mutation zone, reflection and refraction will occur. The reflection wave is accepted by the receiver of the radar system, and the refraction wave continues to propagate in the stratum. Thus, reflection and refraction are generated continuously until the electromagnetic wave energy decays to the point that it cannot continue to propagate. The physical properties of the stratum such as water abundance and fragmentation will affect the electrical properties of the internal medium. Therefore, the geological conditions inside the stratum can be predicted according to the reflected features such as the frequency, amplitude etc. [7].

In effective detection range, GPR has good lateral and longitudinal resolutions, and has high recognition of joints, cracks, cavities, faults, water and other target bodies in the stratum. It is the representative of short-range non-destructive detection technology. Figure 2 shows the detection sketch of GPR, and the black hexagon inside the antenna is the receiver.

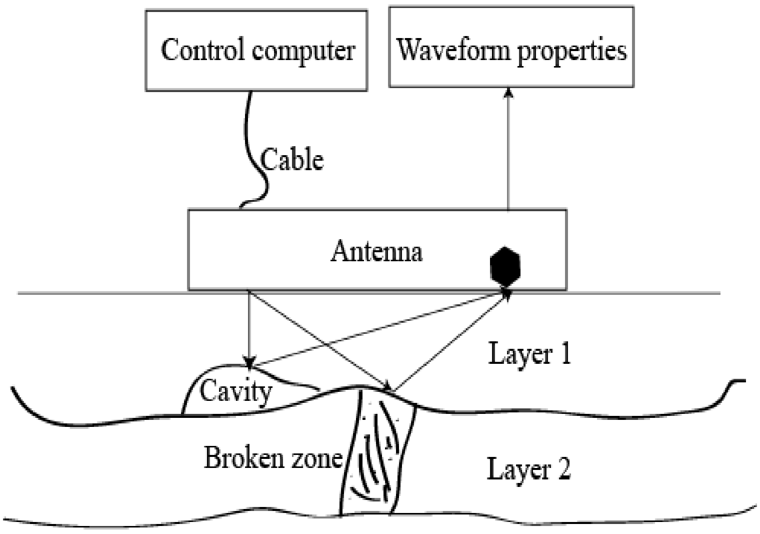

Figure 2: Sketch of GPR detection

3.2. Field Detection and Units Division

Based on the previous geological survey data, the SIR-3000 GPR produced by the United States Geophysical Company was used to detect the slope, and the center frequency of the transmitting antenna was 100 MHz. The detection depth of antenna with this frequency can reach 20-35m, which can completely detect the geological conditions inside the slope and meet the depth requirements.

The slope was relatively steep, which can easily lead to the rapid decline of the antenna in the vertical movement process, which can not accurately control the movement speed and cause invalid detection. Therefore, only horizontal measuring points and lines were set along the direction of the road

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center line. The length of the measuring line was 7-8m, and the vertical spacing was 3m. The number of measuring points depends on the difficulty of field operation, and the spacing was 1-2m. In order to detect the slope completely, besides arranging measuring points and lines on the slope surface, measuring points were arranged in the range of 3-7m around the slope to expand the detection range. Tab.1 shows the detection parameters.

Table 1: Field detection parameters

NO.	Parameters	Values
1	Center frequency(*MHz*)	100
2	Emissivity(*KHz*)	50
3	High-pass filter value(*MHz*)	25
4	Low-pass filter value(*MHz*)	300
5	Time window(*ns*)	600
6	Number of gain points	5
7	Stacking multiplicity	7
8	Relative dielectric constant	5-7

After the detection, the RADAN7.0 GPR analysis software was used to process the original data in time and frequency domain, such as background removal, filtering, and Kirchhoff migration. After statistical analysis, 91 effective detection images were obtained (shown in Figure 3). Based on the comprehensive analysis of the previous geological survey data and the information of amplitude, clarity, co-phase axis, wave velocity and main frequency in the detection image, the water abundance and fragmentation of the slope were predicted, and the slope was divided into units accordingly.

Finally, the slope was divided into eight units, including three V-level units, three IV-level units and two III-level units. The V-level unit was located in the middle and right of the lower step of the slope, the IV-level unit was located in the middle and right of the upper step of the slope, and the III-level unit was located in the left of the upper and lower steps. After this step, the mechanical parameters of each unit were initially assigned according to the suggestion of rock classification standard (GB/T50218-2014, China).

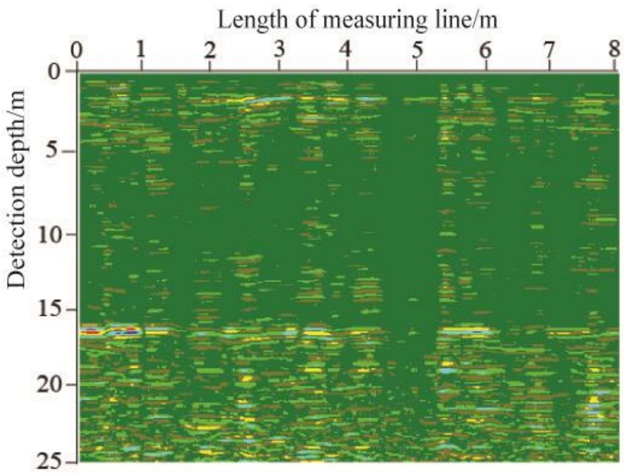

Figure 3: Line-scan detection image

4. Finite Element Numerical Simulation

4.1. Grid Model Establishment

Based on the above analysis, MIDAS-GTS was used to establish the grid model of the slope and calculate the overall displacement to predict the sliding stability of the slope. At the same time, the field displacement monitoring was used to verify and compare the calculation results.

The grid model was established according to the actual range of the whole slope, the transverse width was 32 m and the vertical height was 12.7 m, which was also divided into two steps. The constraint in X direction and Y direction was respectively set on both sides of the model and at the

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bottom, and the slope surface was free surface without constraint. The quadrilateral element was used to generate the grid, and considering the actual differences in the fragmentation and water-richness of different units of slope rock mass, the grid element was not equidistant, but the grid of IV and V-level units was encrypted to improve the transmission efficiency of node parameters, and the encryption ratio was 1:1.3 [8]. Assuming that the rock mass was a homogeneous elastic-plastic body, the Mohr-Coulomb stress criterion was obeyed [9]. Without setting a fixed number of iterations, the software calculates itself according to the principle that the stress distribution reaches equilibrium [10]. Figure 4 shows the established grid model.

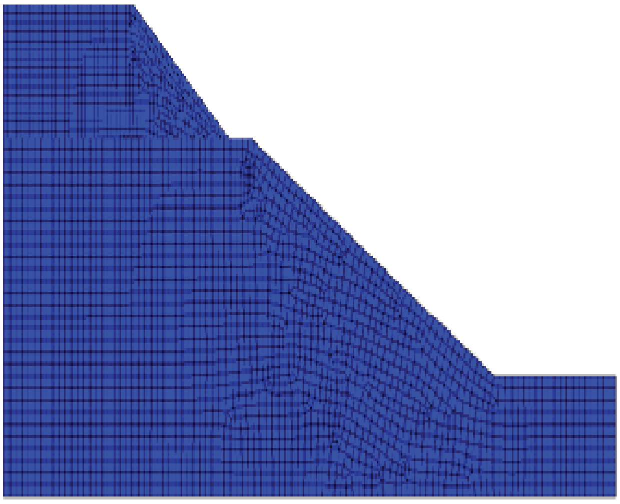

Figure 4: Grid model

4.2. Results Analysis

The color contour shows the macroscopic displacement trend of the whole slope, which cannot shows the displacement value and dynamic change characteristics of a certain unit, and has little effect on the analysis of the displacement change characteristics of micro unit. Therefore, in order to obtain the displacement values of different units, the built-in node extraction technology was used to extract the displacement of different units. To speed up the extraction, a node was extracted from each unit. Tab.2 shows the extraction results under different mechanical parameters.

Table 2: Extraction values of units displacement

No.	Level	Sliding displacement (mm)
1	III	3.96
2	V	9.05
3	IV	7.82
4	III	4.99
5	IV	7.92
6	V	7.96
7	IV	7.55
8	V	8.13

To verify the above results in Tab.2, the SZZZX-N400B displacement meters with the accuracy of 0.01 mm were used to carry out the displacement field monitoring for 28 days immediately. In order to prevent the displacement meters from falling off and thus affect data acquisition, special attention should be paid to not installing the displacement meters on the structural surface or adjacent to it, so those meters were completely staggered from the structural surface and installed on the unit blocks. After the monitoring, the collected data were statistically analyzed, and the results showed that the sliding displacements of unit 1-8 rock units were 4.12 mm, 9.2 mm, 7.90 mm, 5.1 mm, 8.0 mm, 8.2 mm, 7.63 mm and 8.32 mm, respectively.

It can be seen that the simulated calculation value of displacement is closer to the measured one, indicating that the mechanical parameters obtained by GPR spot detection are more reliable. It should be noted that the simulated displacement is less than the measured one, which is because the

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deformation range and direction of rock mass are limited in simulation calculation, while the real rock mass is three-dimensional deformation state.

5. Conclusion

In this paper, a finite element numerical simulation method of rock slope based on GPR field detection is proposed. Facts and figures show that when grading the natural rock mass according to the specification, it is necessary to consider the differences in physical properties such as water abundance and fragmentation. The unit division based on GPR field detection can better avoid the subjective and empirical influence on grading, and more reliable mechanical parameters can be obtained.

Acknowledgements

This work was supported in part by the Science and Technology Research Project of the Education Department of Jiangxi Province under Grant GJJ204903.

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