Detection of a Weak Structural Stratum and Stability Analysis of the Slope in an Intensely Weathered Open-pit Mine

Jianlin Luo¹², Wentao Zhu¹⁴*, Changbo Xiao¹⁵, Jian Ouyang¹³, Zhiqi Feng¹, Qi Shuai¹, Zequn Zhang¹ and Wen Zhong¹³⁴*; ¹School of Resources and Environment Engineering, Jiangxi University of Science and Technology, Ganzhou 341000, China; ²Jiangxi college of Applied Technology, Ganzhou 341000, China; ³Chongyi Zhangyuan Tungsten Co., Ltd., Ganzhou 341300, China; ⁴State Key Laboratory of Geotechnical Mechanics and Engineering, Wuhan Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China; ⁵Jiangxi Zhongliang Blasting Engineering Co., Ltd., Pingxiang 337000, China; *Author to whom any correspondence should be addressed: Wen Zhong: wzhong@jxust.edu.cn; Wentao Zhu: zansel112@163.com ORCID: https//orcid.org/0000-0003-2035-6293

Abstract. Within the mining boundary of an open-pit mine located in southern China, due to the intense weathering of the slope rock stratum, the quaternary loose soil layer and soft rock stratum, karst cavity and water-bearing weathered-fracture zone and other weak structural strata have posed a great threat to the side slope stability of open-pit mining. Using the Flashres64 Multichannel Ultra-High-Density Electrometer to conduct on-site detection of the slope, based on the spatial distribution of the low-resistance layer and the drilling geological data, this study interpreted the stratum lithology of the slope and conducted effective identification of the weak structural stratum. Furthermore, according to the Hoek–Brown Failure Criterion, the Flashres64 reduced the strength of the mechanical parameters of the rock-soil and weak structural stratum of the slope, and imported the relevant data into the SLIDE software for slope stability analysis. The results showed that this method could make advanced macro-predictions of the weak structural stratum occurring in intensely weathered slopes. The slope stability analysis results considering the adverse effects of the weak structural stratum were also highly consistent with the actual engineering situation, for which the application is worth promoting in related fields.

1. Introduction
The geomagnetic field influences the formation of different reflecting waves of a magnetic field. Therefore, we can inversely derive different geomagnetic characteristics for different formation lithology by measuring the reflecting magnetic field for the formation of different depths[1-5]. The Flashres64 Multichannel Ultra-High-Density Electrometer adopts a multichannel and multielectrode full-waveform data acquisition method, and acquires conductivity or resistivity soundings by gathering electromagnetic waves of the geomagnetic field, and works to find out the anomalous body by analysis. This system is based on the basic theory of the geomagnetic field, a combination of CSAMT and MT...
belongs to a magnanimously sounding system and it is internationally the most advanced method for electromagnetic investigation at present[6-10]. There is a positive and long-term understanding of stability analysis of strongly weathered slopes that lead to identification for distribution of unidentified weak interfaces in strongly weathered slopes using Flashres64.

2. Components and procedures

2.1 Components
Flashres64 is composed of three parts: the launching system, the receiving system, and the controlling system (Fig.1). The launching system consists of the transmitter, antenna, and controller; the receiving system consists of preamplifier, electromagnetic sensors, and accessory equipment; and the controlling system consists of a master control and system software. The system software performs two main functions, namely, data acquisition control and data processing. A sketch of the Flashres64 data acquisition unit is illustrated in Fig. 2.

In the field detection process, we first determined the measuring lines and survey stations through a geological survey followed by drawing a measuring map. Then, we constructed a coordinate system oriented at the survey station. The $E_{x0}-E_{x1}$ is the $x$-height and the $E_{y0}-E_{y1}$ is the $y$-height; the electrode spacing is 30 m between $E_{x0}-E_{x1}$ and $E_{y0}-E_{y1}$. The bar magnets $H_{x0}-H_{x1}$ and $H_{y0}-H_{y1}$ are laid vertically in any quadrant of coordinate system posed electrodes; the distance between bar magnets $H_{x0}-H_{x1}$ and $H_{y0}-H_{y1}$ is at least equal to 2 m; the distance between the joint of the magnetic pole and analog front end is at least equal to 5 m; the distance between the transmitting antenna and analog front end and the distance between two survey stations is at least equal to 200 m, as shown in Fig. 3.

![Figure 1. Engineering rock mass geology exploration](image1)

![Figure 2. A sketch of Flashres64 data acquisition unit](image2)

![Figure 3. The measuring map of field detection using the Flashres64](image3)
2.2 Interpretation
Different time detection results are relatively stable based on the same circumstance or similar circumstances in the same geographic location on the earth\cite{11}. This theory provides a scientific basis for the geomagnetic method for investigation\cite{12-14}. Resistivity has a great deal to do with the moisture content because water is a good conductor\cite{15-17}. The higher the moisture content and the salt in water, the lower the resistivity is, and vice versa. Apparently due to the strongly weathered broken loose rock abounding in water, the resistivity is very low. Thus, for a loose formation, water-filled or mud-filled geological structure, the resistivity is usually low, but in karst caves without other medium fill or water fill, the resistivity is usually high. Therefore, we can judge the abnormalities of the underground geological structure qualitatively if we analyze the detected data of abnormal areas considering low and high resistivities. The judgment on lithology based on resistivity depends on drilling data. Normally, we compare according to the drilling bar chart with the resistivity sounding section of the drilling position. Then, we judge the formation of lithology using the corresponding resistivity sounding.

However, because the geomagnetic detection depth usually reaches as far as 1000 m, deep hole drilling is prone to drill deflections at certain stages along deep depths. This tends to introduce errors into the interpreted results dependent on deep drilling data. Therefore, information obtained on shallow borehole data is more reliable than that at greater depths.

3. Case study

3.1 Weak interfaces exploration
A second-phase mining slope in an open-pit mine in southern China was studied. It is a multmetal open-pit mine predominantly mines for copper and sulfur. In the mining area, the terrain weathering activity is strong. The fractured structure includes drape, faults and fissures. Because the mining area is near a lake, there is surface water; also, the groundwater is rich in limestone and there are intrinsic factors of engineering geology disaster in the mining area that include quaternary loose cover, karst cave, weathering fracture zone, and other bad geographic geological environments.

The slope of detection is located in the northeast of the slope, the trend of the slope is north–south, the dip direction of the slope surface is situated westward, and the slope angle of practical steps is about 70°. The engineering geological rock group type of the slope is granodiorite–porphyry. Because of the strong weathering activity in the exposed upper slope, the kaolinite present is almost a loose structure. The potential failure mode of the slope is circular in nature and because there are karst caves in the slope, karst collapse is locally visible.

This measuring line arrangement is with the #3 geological exploration line in the mining area, there are 12 survey stations altogether. The coordinates of survey station 1 are (3285860.9, 383417.6, and 8.5); the azimuth angle is NW328°, and the measuring point spacing is 30 m. The main components of the fill soil within the measuring area contain all kinds of weathering products of rock and ore and quaternary loose cover. The under-part is deposit of lacustrine clay. The bedrock includes granodiorite–porphyry, quartz porphyry and limonite. The measuring line schematic is illustrated in Fig. 4.

According to mine data, effective drilling that can be adopted for this detection-calibrating basis consists of ZK310, ZK311, ZK312 and ZK992. The idea is to assign some sections in the drilling path as calibrating sections. The distribution of the resistivity with calibrating sections along the measuring line is shown in the following Table.1 and Fig. 5. The resistivity of calibrating sections along the measuring line ranges from 7 m to 193 m. Although the resistivity is small, the change in the resistivity is great in the formation. Thus, a complex 2-D resistivity section was constituted to expose intricate weak interfaces on every calibrating section.
Figure 4. The measuring line schematic

Figure 5. Resistivity–depth relational graph

Table 1. The statistics of the resistivity with calibrating sections along the measuring line.

| Depth (m) | Resistivity (Ω·m) | Depth (m) | Resistivity (Ω·m) | Depth (m) | Resistivity (Ω·m) | Depth (m) | Resistivity (Ω·m) |
|----------|-------------------|----------|-------------------|----------|-------------------|----------|-------------------|
| 0–10     | 26                | 0–62     | 13                | 0–10     | 13                | 0–20     | 51                |
| 10–30    | 51                | 62–108   | 26                | 10–244   | 51                | 20–42    | 26                |
| 30–42    | 26                | 108–116  | 51                | 244–360  | 13                | 42–58    | 51                |
| 42–76    | 13                | 116–200  | 13                | 360–610  | 51                | 58–100   | 100               |
| 76–80    | 26                | 200–244  | 7                 | 100–130  | 193               | 130–170  | 100               |
| 80–180   | 193               | 244–288  | 51                | 130–170  | 100               | 170–190  | 193               |
| 180–280  | 51                | 288–348  | 26                | 170–190  | 193               | 190–820  | 100               |
| 280–388  | 100               | 348–388  | 51                | 190–820  | 100               | 820–870  | 193               |
| 290–388  | 51                | 388–390  | 100               |          |                   |          |                   |
| 388–390  | 100               |          |                   |          |                   |          |                   |
Based on the data in Table 2, the resistivity located in the intermediate locations of the measuring line is lower than 51 m. There are abnormalities in parts of the nearby slope; their resistivities are above 100 m with a subsequent range of depths of 80 to 180 m, 280 to 299 m and 388 to 390 m. The resistivity of sections near the lake is less than 51 m with a depth range of 0 to 58 m. Through interpretation, the low-resistance parts located in shallow formations are mainly of compounds of clay, clinosol, alluvial mild clay and alluvial clay. The low–resistance parts located in other formations consist mainly of weathered dacite, quartz porphyry, limestone and granodiorite–porphyry. The high–resistance sections consist mainly of pyritization quartz porphyry, moderately weathered quartz porphyry, and granodiorite–porphyry.

Despite all resistances being generally low, there are still substantial differences worth noting. Resistance to weathering is different because of the difference in lithology. It thus forms a particular formation configuration that alternates from shallow low–resistance to deeper low–higher–resistance, while the high–resistance formation is mainly due to the influence of quartz porphyry. Therefore, in potential failure modes for the slope, besides main circular failure, there are still local small-scale collapse sections including polylines and landslides. The interpretation section diagram of the geological formation is illustrated in Fig. 6.

| Nearby slope | Intermediate locations | Nearby lake |
|--------------|------------------------|-------------|
| Depth (m)    | Resistivity (Ω⋅m)      | Depth (m)   | Resistivity (Ω⋅m) | Depth (m) | Resistivity (Ω⋅m) |
| 0–80         | <51                    | 0–610       | <51                 | 0–58      | <51                 |
| 180–280      | <51                    | -           | -                    | -         | -                    |
| 299–388      | <51                    | -           | -                    | -         | -                    |

Table 2. The statistics of abnormalities resistivity

Figure 6. Interpretation section diagram of geological formation

3.2 Slope stability analysis
Interpretation analysis shows that the weak interfaces of the slope are primarily shallow overburden, varved clay, and strongly weathered breccia. The shear strength form of the Hoek–Brown criterion (expression (1)) is adopted to obtain the strength parameters of the various rock-and-soils of the slope and that of weak interfaces after strength reduction. Table 3 presents the physical mechanical parameters of various rock-and-soil of the side slope and the weak interfaces.
\[ \tau = \frac{1}{8} m \sigma_c (\cot \phi'_i - \cos \phi'_i) \]

where \( \tau \) is shear strength, \( \phi'_i \) is the instantaneous effective inner fraction angle.

\( \phi'_i \) can be represented as follows:

\[ \phi'_i = \arctan \left( 4a \cos^2 \left[ 30^\circ + \frac{1}{3} \arcsin (a) \right] \right) ^{1/2} \]

\[ a = 1 + 16 \left( m \sigma_n + s \sigma_c \right) \sqrt{3m^2 \sigma_c} \]

**Table 3.** The strength parameters of the various rock-and-soil of the slope and that of weak interfaces after strength reduction

| Rock-and-soil                        | \( \Phi/c^\circ \) | c/MPa |
|--------------------------------------|--------------------|-------|
| Primarily shallow overburden         | 18.9               | 0.080 |
| Alluvial clay, Varved clay           | 15.3               | 0.027 |
| Strong weathered breccia             | 12.2               | 0.078 |
| Strong weathered limestone           | 11.6               | 0.705 |
| Strong weathered quartz porphyry     | 18.4               | 0.977 |
| Weathered granodiorite-porphyry      | 18.2               | 0.969 |
| Weathered skarn                      | 14.7               | 0.836 |
| Weathered pyrite                     | 19.1               | 1.003 |
| Weathered limonite                   | 16.8               | 0.914 |
| Weathered magnetite                  | 19.7               | 1.121 |
| Weathered molybdenite                | 14.3               | 0.876 |
| Weathered dacite                     | 15.6               | 0.932 |

After introducing the geological model of the weak structural ascertained layers into SLIDE, a material model is established with the physical mechanical parameters inputted. Ground motion acceleration is set at 0.05 g in accordance with the real conditions of the mining area, and the tramcar load is assumed 150 kN/m² in consideration of the practical demand of the large-scale mining. The slope stability analysis model is set up as shown in Fig. 7.

The Simplified Fellenius, Simplified Bishop and Simplified Janbu methods are chosen for the analysis. Global slope stability is analyzed first, after which the nine slope benches were analyzed one-by-one. Figure 8 shows the analytic results while Fig. 9 and 10 present the results of the slope stability analyses of some benches using the Simplified Janbu method.

**Figure 7.** Slope stability analysis model
Figure 8. Stability analysis Global slope (Simplified Janbu method)

Figure 9. 2# slope bench stability (Simplified Janbu method)

Figure 10. 3# slope bench stability (Simplified Janbu method)

Table 4. The safety factors of slope stability computed using the three methods

| Slope benches | Simplified Fellenius method | Simplified Bishop method | Simplified Janbu method |
|---------------|-----------------------------|--------------------------|-------------------------|
| Global        | 0.748                       | 0.758                    | 0.721                   |
| 1             | 3.006                       | 3.005                    | 3.005                   |
| 2             | 1.502                       | 1.500                    | 1.502                   |
| 3             | 3.446                       | 3.444                    | 3.449                   |
| 4             | 3.911                       | 3.909                    | 3.918                   |
| 5             | 3.046                       | 3.048                    | 3.037                   |
| 6             | 18.391                      | 18.393                   | 18.240                  |
| 7             | 16.157                      | 16.156                   | 16.175                  |
| 8             | 14.700                      | 14.698                   | 14.733                  |
| 9             | 22.417                      | 22.416                   | 22.441                  |
Table 4 shows that the safety factors computed by the aforementioned three methods are consistent. All nine benches have a safety factor greater than 1.5 and they are stable according to Chinese specifications for geotechnical engineering. However, the overall slope has a safety factor of less than 1.0, which indicates its global instability.

4. Conclusion
According to the practical application of Flashres64 for engineering geological exploration in an open-pit mine, we know that Flashres64 has advantages such as being immune to the effect of high resistivity layer shielding, stable performance, lightweight, convenient, simple construction, and low-cost features. Therefore, it is highly suitable for exploring weak interfaces in a weathered slope. According to the results, we can effectively recognize the incised formation structure and faults, broken belts, concealed karst areas, water-rich areas or unfavorable geological bodies. These conclusions can be used to classify slope stability analysis. Interpretation analysis shows that the weak interfaces of the slope are primarily shallow overburden, varved clay, and strongly weathered breccia. This exploration of weak interfaces can be a benchmark for further prospective studies of weathered slope stability.

5. References
[1] Kim, Y., Lee, S., Jeong, S., & Kim, J. (2013). The effect of pressure-grouted soil nails on the stability of weathered soil slopes. *Computers and Geotechnics, 49*, 253-263.
[2] Kim, D. H., Gratchev, I., & Balasubramaniam, A. (2015). A Photogrammetric Approach for Stability Analysis of Weathered Rock Slopes. *Geotechnical and Geological Engineering, 33*(3), 443-454.
[3] Sato, S., Goto, T.-n., & Koike, K. (2020). Spatial gradients of geomagnetic temporal variations causing the instability of inter-station transfer functions. *Earth, Planets and Space, 72*(1).
[4] Liu, C., Xin, Q. U., Feng, X., Tian, Y., Liu, Y., Qiao, H., & Wang, S. (2017). Application of high-frequency magneto telluric method in porphyry copper deposit exploration: a case study of Duobaoshan deposit area. *Global Geology, 020*(004), 246-252.
[5] Pires, A. C. B., Carmelo, A. C., & Martins-Ferreira, M. A. C. (2019). Statistical enhancement of airborne gamma-ray uranium anomalies: Minimizing the lithological background contribution in mineral exploration. *Journal of Geochemical Exploration, 198*, 100-113.
[6] Srivastava, A. (2012). Spatial Variability Modelling of Geotechnical Parameters and Stability of Highly Weathered Rock Slope. *Indian Geotechnical Journal, 42*(3), 179-185.
[7] Han, G., Liu, X., & Wang, E. (2013). Experimental study on formation mechanism of compaction bands in weathered rocks with high porosity. *Science China Technological Sciences, 56*(10), 2563-2571. doi:10.1007/s11431-013-5322-2
[8] Omar, H., Pauzi, N. I. M., Abu-Shariah, M., Yusoff, Z., & Maail, S. (2009). Microcracks pattern and the degree of weathering in granite. *European Journal of Government and Economics.*
[9] Zhong, W., Tan, Z., Li, Y., & Li, X. (2011). Application of EH-4 in field investigation of engineering geology for strongly weathered slope. Paper presented at the The 2nd ISRM International Young Scholars’ Symposium on Rock Mechanics.
[10] Jingtian Tang, Y. W., Xiao Xiao, Jifeng Zhang. (2007). Study of the High Frequency Magneto telluric Sounding for Prospecting the Deep and Periphery Mine by RRI Inversion *Progress In Electromagnetics Research Symposium Online (PIERS Online), 3*(1).
[11] Woo, I., Fleurisson, J.-A., & Park, H.-J. (2010). Influence of weathering on shear strength of joints in a porphyritic granite rock mass in Jechon area, South Korea. *Geosciences Journal, 14*(3), 289-299. doi:10.1007/s12303-010-0026-0
[12] Abad, S. V. A. N. K., Mohamad, E. T., Komoo, I., & Kalatehjari, R. (2015). A typical weathering profile of granitic rock in Johor, Malaysia based on joint characterization. *Arabian Journal of Geosciences, 8*(4), 2191-2201.
[13] Susilo, A., Sunaryo, & Isdarmadi, K. (2017). Investigation of Jabung Temple subsurface at Probolinggo, Indonesia using resistivity and geomagnetic methods. *International Journal of*
[14] Bikku, T., Kpnv, S. S., Gnanasekar, & Deivakani. (2021). Nonlinear regression framework for geomagnetic data restoration analysis through machine learning techniques. *Materials Today: Proceedings*.

[15] Rasul, H., Zou, L., & Olofsson, B. J. N. S. G. (2018). Monitoring of moisture and salinity content in an operational road structure by electrical resistivity tomography. *NEAR SURFACE GEOPHYSICS, 16*, 423-444.

[16] Brindha, K., Elango, L., & Nair, R. N. (2011). Spatial and temporal variation of uranium in a shallow weathered rock aquifer in southern India. *Journal of Earth System Science, 120*(5), 911-920.

[17] Wang, P., Wu, Z., Wang, J., Zhang, Z., & Wang, Q. (2013). Experimental study on mechanical properties of weathered rock covered by loess. *Journal of Shanghai Jiaotong University (Science) volume, 18*, 719-723.

**Acknowledgements**

The authors gratefully acknowledge the financial support from the Project supported by the China National Key R&D Program during the 13th Five-year Plan Period (No. 2017YFC0804601), Natural Science Foundation of China (No.51764014), Open Foundation projects of the State Key Laboratory of Geomechanics and Geotechnical Engineering (No.Z017024), Natural Science Foundation of Jiangxi Province (No.2019BAB206018), General Program Supported by China Postdoctoral Foundation (No.2017M622099) and Jiangxi Province young Jinggang scholars Award Program (No.QNJG2019054).