DFOS-based association rules analysis on the multi-fields information of Majiagou landslide

Lei Zhang1, Bin Shi1,*, Xing Zheng1, Yi-Jie Sun2

1 School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China
2 College of Transportation Science and Engineering, Nanjing Tech University, Nanjing 211816, China

* Corresponding authors’ e-mail: shibin@nju.edu.cn (B.S.)

Abstract. The multi-fields information of landslide can be obtained using distributed optical fiber sensing (DFOS) technology. Nevertheless, it is still a quite complicated work to analyze massive amounts of multi-fields information, and to evaluate the slope stability under multi-fields coupling effect. This paper introduced a data mining method named association rules analysis, and designed a DFOS-based monitoring system to record the multi-field information, including strain field, deformation field, seepage field, temperature field and environmental parameters, respectively. Taking Majiagou landslide as an example, the association rules analysis of the multi-field monitoring information revealed the reservoir water level is the domain factor that influences the deformation of Majiagou landslide. The correlation analysis method can explore the internal relationship among different fields of a landslide and provide scientific basis for slope stability evaluation and landslide early-warning.

1. Introduction
Reservoir landslide is an open complex system composed of solid, liquid, gas multiphase, and it changes with the action of multi-fields. The stability of a reservoir landslide is affected by many factors such as rainfall, water level fluctuations, manmade disturbances, and temperature variation, etc. Rainfall and reservoir water level fluctuations can periodically change the seepage field of a landslide. The landslide stability condition was affected by the pore water pressure and seepage force acting on the soil or rock. Temperature can influence the landslide equilibrium state by changing the shear strength of the soil[1]. In general, the deformation of soil in a landslide is the result of interactions of many factors, which if understood, can help in evaluation and prediction of landslide stability. Therefore, in order to explore the internal relationship among different factors, the multi-fields information of the landslide should be obtained.

In the past decades, the fiber optic sensing technology has been developed for monitoring deformation and other impulses[2]. Fiber optic sensors have some unique advantages over traditional transducers (i.e. strain gauges, piezometer, thermometer, etc.), including its immunity to electromagnetic interference, high precision, online monitoring and the ability of multi-plexing[3]. Consequently, the technique has been successfully used in the field of geotechnical engineering. Internal deformation and the failure of a centrifuge model slope was investigated with horizontally and vertically embedded FBG arrays[4]; A laboratory test with buried FBG sensors was performed and the
evolutionary process of the model slope was analyzed using monitored physical information[5]. A model slope test was carried out based on DFOS technology and the monitoring information related to slope stability demonstrates that the DFOS technologies are especially configurable for laboratory-scale tests[6]. The development of distributed fiber sensors and their integration into geosynthetics that were used for dike construction and flood protection were reported[7]. An early-warning system was established and stability condition was evaluated by recording water level fluctuation and pressure changes in a soil slope with FBG technology[8].

Huge amounts of the multi-field information can be monitored using DFOS technology. How to find out the internal relationship, especially dig out the correlation among multi-fields, is not easy. Because the relationship between the multi-fields of the reservoir landslide is nonlinear, the traditional mathematical methods such as fitting method and comparison method are not applicable. Association rule analysis method is a nonlinear dynamic system, which can automatically summarize and classify a large amount of data, and obtain effectively reflect the implicit nonlinear relationship among different factors. Additionally, the association rule analysis method can avoid calculating the safety factor, and is widely used in solving nonlinear problems.

The Majiagou landslide, a traditional reservoir landslide located in Three Gorges Region was introduced in this paper. The strain field, deformation field, seepage field, temperature field and environmental parameter of Majiagou landslide were recorded using DFOS technology. A data mining method- association rule is utilized to explore the internal relationship among different fields. The results show that association rules can effectively dig out the implicit relationship among multi-fields and provide a scientific way to deal with huge amount monitoring data.

2. Association rules analysis method

Association rule is one of the most classical data mining method, which is mainly used to explore the interrelations hiding in dates. Apriori algorithm, the commonly used association rule method, was adopted in this paper [9].

Suppose $I = \{i_1, i_2, ..., i_m\}$ is a collection that contains several property field. The elements in $I$ called items. Suppose $D$ is the collection of transaction $T$, $T$ is a collection of all occurrence in a transaction, and $T$ is the subset of $I$.

In a transaction database $D$, a transaction rule is the implication just like $X \Rightarrow Y$, $X \subset I$ is the antecedent of this association rule; $Y \subset I$ is the consequent, and $X \cap Y = \emptyset$.

Define support:

$$Support(X \Rightarrow Y) = \frac{|\{T : X \cup Y \subseteq T, T \in D\}|}{|D|}$$  \hspace{1cm} (1)

Define confidence:

$$Confidence(X \Rightarrow Y) = \frac{|\{T : X \cup Y \subseteq T, T \in D\}|}{|\{T : X \subset T, T \in D\}|}$$  \hspace{1cm} (2)

The association rule mining problem is to generate association rules with support and confidence greater than the minimum support and minimum confidence set by the user, respectively. If the support and confidence of the rule are greater than the threshold given by the user, then the rule is a strong association rule; otherwise, the rule is a weak association rule. The main problem of the association rule analysis method is to find all strong association rules in the database [10]:

When processing multi-fields data, it is necessary to carry out targeted operations according to the specific mining environment. This paper summarizes the general steps of association rules, as shown in Figure 1. It solves the difficulties of how to adjust the landslide multi-field data into a data structure that the software is capable of, how to reasonably divide the data according to the geological characteristics of the landslide, and how to select appropriate monitoring data for association rule analysis.
3. Acquiring multi-fields information of landslide

3.1. DFOS technology of acquiring landslide multi-fields information
At present, the commonly used DFOS technologies mainly contain Fiber Bragg Grating (FBG), Brillouin Optic Time-Domain Reflectometer (BOTDR), Brillouin Optic Time-Domain Analyzer (BOTDA), Raman Optic Time-Domain Reflectometer (ROTDR), and so on. The FBG and BOTDR technologies, which can achieve single-ended measurement, are suitable for the in-situ monitoring. The working principle are described detailly by Zhang [11].

3.2. Monitoring scheme design of acquiring landslide multi-fields information
Landslide is an open system, it is affected by multiple internal and external factors. In order to evaluate the stability and investigate the developing law of a landslide, the relevant multi-fields information need to be obtained first.

3.2.1. Strain field monitoring
Strain can be monitored using the distributed strain sensing (DSS) cable. For the strain field monitoring, there are three layout modes. First, the DSS cable can be pasted onto the anchor rod and cable body, fixed by bonding and then implanted into the rock and soil mass [12]; Second, the DSS cable can be woven into geogrid, geotextile and then filled into the soil to monitor the soil deformation and internal force distribution of geotextiles; Third, the DSS cable can be implanted into anti-slide piles so as to monitor the deformation and internal force distribution along the piles.

3.2.2. Deformation field monitoring
The displacement field is the cumulative reflection of strain in space. Landslide displacement can directly reflect the landslide boundary and deformation pattern. The landslide displacement can be recorded by using DSS cables. The DSS cable is fixed with an interval of 20cm, the rest is loosely isolated to measure the relative displacement between the two points. As shown in Figure 2, the DSS cable is arranged approximately orthogonally along the contour line.
3.2.3. **Seepage field monitoring**

The monitoring of the seepage field can be achieved using distributed temperature sensing (DTS) technology. The water content in the landslide will directly change the heat transfer performance of the soil. The higher the water content, the stronger its thermal conductivity. Among them, for the flow field where there is a free water level, the burial depth of the flow water level can be determined according to the heating rate difference along the DTS cable in the longitudinal direction.

3.2.4. **Temperature field monitoring**

The temperature field of the landslide can be monitored by embedded DTS cables. The temperature field of the entire slope can be monitored by embedding multiple sets of DTS cables in different locations, different directions, and different depths. In order to save costs and facilitate construction and post-maintenance, optical fiber sensing (OFS) comprehensive monitoring boreholes can be arranged along the main sliding direction of the slope. The comprehensive monitoring borehole can achieve temperature, pore water pressure, deformation and strain measurement. As shown in Figure 3.
3.2.5. Environmental parameter monitoring

a) Rainfall monitoring
Rainfall, especially heavy and long-term rainfall, have been widely recognized as important factors triggers landslides. Statistics data showed that rainfall in Three Gorges Region were mainly concentrated in June, July, August, and September [13]. The mechanism of rainfall triggers landslides can be attributed to the matrix suction. The high-intensity and long-term rainfall infiltration decrease the matrix suction of the slope soil and the shear strength therefore decreases. Daily rainfall data were collected by a weather station (Fig.4) that was installed on the Majiagou landslide. The monitoring results can be transmitted to the control center via the GPRS module.

![Figure 4. The weather station](image)

b) Reservoir water level monitoring
The change of reservoir water level is directly related to the dynamic seepage field, pore water pressure field and seepage velocity field distribution of the slope. Reservoir water level fluctuations can periodically change the seepage field of a landslide[14]. The landslide stability condition was affected by the pore water pressure and seepage force acting on the soil or rock[15].

The daily reservoir water level was measured by the Hydrology Bureau of Changjiang Water Resources Commission and presented at the website (http://www.cjsyw.com).

4. CASE STUDY

4.1. Overview of Majiagou landslide
The Majiagou landslide, initiated when the reservoir was first impounded in 2003, is 560m long, 180-210m wide. It is situated on the left bank of the Zhaxi River, a tributary river of the Yangtze River in Zigui County, Hubei Province (Fig.5). The front of the landslide is a fluvial alluvial terrace and forms multi-stage gentle platform and steep sided ridges. Its average gradient is approximately 15°.

The Majiagou landslide are mainly constituted of surficial deposits and sedimentary bedrock. The surfical deposits is mainly composited of residual silty clay with gravels interbedded with little sandstone. The bedrock, with dip direction of 270-290° and dip angle of 25-30°, comprises quartz sandstones interbedded with thin silty mudstones of the Jurassic Suining Formation. The silty mudstone can be easily softened by water and is highly fractured. It is one of the most common sliding strata in the TGR region. The annual rainfall and reservoir water level fluctuate seasonally. Nearly 70% of the
rainfall is concentrated in period of May-September, and the water level in the reservoir fluctuates annually from 145m to 175m.

4.2. Monitoring scheme
The monitoring program is implemented mainly by deploying optical fiber sensors embedded in comprehensive monitoring boreholes, anti-slide piles, and drain ditches. After installation, all the sensors were introduced to the monitoring station to realize the centralized data collection. The specific monitoring plan and layout method were introduced by Sun[16]. The data acquisition started in September 2012 and was conducted at an interval of about 1-3 months.

![Figure 5. Layout of fiber optic sensors](image)

4.3. Analysis results of association rules
Taking into account the geological characteristics of Majiagou landslide, Boreholes OFS1, OFS2, OFS3, JC1, JC3 and JC8 were selected as subjects (Figure 5), which are 6 comprehensive monitoring boreholes located at the front, middle and rear edges of the landslide, respectively. In the analysis of association rules, there are 8 variables, including rainfall, rainfall change, reservoir water level, reservoir water level change, temperature, temperature change, displacement rate and displacement rate change. Table 1 shows partial data. It is noted that due to the lagged variation of rainfall infiltration and changes of reservoir water level, the monitoring data 10 days ago were selected to carry out this study.

In this paper, the data mining association rule method is used to analyze the multi-field information of Majiagou landslide. There are mainly two steps. The first step is to organize the multi-field data into the database and iterate to retrieve all frequent item sets in the database. That is, an item set with a support level of not less than 20%; The second step is to use frequent item sets to construct a rule with a confidence level of not less than 60%.
Table 1. Data processing of the landslide multi-fields monitoring information

| Monitoring parameters | Data classification | Identification | Monitoring parameters | Data classification | Identification |
|-----------------------|---------------------|----------------|-----------------------|---------------------|----------------|
| Rainfall (mm/10d)     | (-∞, 50) [50, +∞)  | 0              | Temperature (°C)      | (-∞, 19) [19, +∞)  | 0              |
| Rainfall change (mm/10d) | (0, +∞) | 0              | Temperature change (°C) | (0, +∞) | 1              |
| Reservoir water level (m) | (135m, 155m) | 0              | Displacement rate     | (-∞, 0.5] | 0              |
|                      | (155m, 175m)       | 1              |                       | (0.5, +∞) | 1              |
| Reservoir water level change (m) | [0, +∞) | 0              | Displacement rate change | (0, +∞) | 1              |

Five strong association rules among multi-fields of Majiagou landslide can be drawn through the above analysis, as shown in Table 2.

Table 2. The result of association rules analysis on the multi-fields data of slope

| Rules     | Antecedent                          | Consequent                        | Support level | Confidence |
|-----------|-------------------------------------|-----------------------------------|---------------|------------|
| Rule 1    | Rainfall increase                   | Displacement rate increase        | 20.0%         | 72.6%      |
| Rule 2    | Reservoir water level increase      | Displacement rate decrease        | 20.0%         | 65.4%      |
| Rule 3    | Low reservoir water level           | Displacement rate increase        | 20.0%         | 72.6%      |
| Rule 4    | High reservoir water level          | Displacement rate decrease        | 80.0%         | 66.9%      |
| Rule 5    | Low temperature                     | Displacement rate decrease        | 20.0%         | 70.6%      |
| Rule 6    | Temperature decrease                | Displacement rate decrease        | 60.0%         | 67.4%      |
| Rule 7    | Reservoir water level increase      | Displacement rate decrease        | 20.0%         | 65.4%      |
| Rule 8    | Reservoir water level increase      | Displacement rate decrease        | 20.0%         | 65.4%      |
| Rule 9    | Reservoir water level decrease      | Displacement rate decrease        | 60.0%         | 67.4%      |
| Rule 10   | Reservoir water level decrease      | Displacement rate increase        | 20.0%         | 72.6%      |

According to the association rules listed in Table 2, some principles can be drawn as follows:

(1) When the reservoir water level rises, the displacement rate decreases; When the reservoir water level is low, the displacement rate increases; When the reservoir water level is high, the displacement rate decreases.
rate decreases (rules 8, 9, 10). The height of the reservoir water level has a greater impact on landslide deformation than the fluctuation of the reservoir water level. According to rule 9, when the reservoir water level is at a high level and the reservoir water level decreases, the displacement rate decreases.

The deformation rate is associated to the slope stability, it is considered that the deformation rate increases and the stability decreases, and vice versa. According to the association rules, the reservoir water level is at a low level, which is unfavorable to the stability of the slope. It can be inferred that the rise of the water level is beneficial to the stability of the slope. When the reservoir water level is at a low level, the rise and fall of the water level has a greater impact on the stability of the slope. When the reservoir water level is low and falling, the landslide is in the most dangerous state (Rule 10).

(2) As the rainfall increases, the displacement rate increases (Rule 1), but the impact of rainfall on the deformation field is less important than the reservoir water level. According to Rule 7, the reservoir water level increases, and when the rainfall increases, the displacement rate decreases.

(3) When the slope temperature is low or the temperature decreases, the slope displacement rate decreases (rules 5, 6). When the temperature is high and the temperature rises, the displacement rate increases or decreases. The effect of temperature does not show obvious regularity. According to Rule 8, when the temperature is high and the reservoir water level increases, the displacement rate decreases, indicating that the temperature has less influence on the slope deformation compared to the reservoir water level.

When the reservoir water level drops slowly from high level to low level, pore water pressure is gradually dissipated due to the high permeability coefficient of the superficial deposits, and the change in the pore water pressure inside the slope is consistent with that of the reservoir water level. When the reservoir water level drops rapidly, the pore water pressure inside the slope shows an inadaptable response. Due to the inadequate dissipation of pore water, the transient seepage occurred inside the slope deposits above the water level. Meanwhile, the transient flow inside slope deposits forms seepage force downslope along the slip direction, thereby accelerating the deformation of the landslide. When the reservoir water level remains at low level, the lag respond of water from the rear edge of the landslide will recharge the front edge. Under the combined action of rear edge seepage and intensive rainfall, the seepage force pointed to the exterior of the landslide accelerated the deformation of the landslide.

5. Conclusions
In this paper, the association rule method is used to analyze the multi-fields information of Majiagou landslide, and the following conclusions are shown as follows:

- By applying the association rule method, the multi-field information of the landslide can be mined from the perspective of data association, revealing the hidden regularity of Majiagou landslide.
- After analyzing relationship between the multi-fields (seepage, temperature) and deformation fields, all the fields are related to the deformation field, and the reservoir water level is the dominant factor that control landslide deformation.
- The reservoir water level and its fluctuation velocity affect the stability of Majiagou landslide by changing the seepage field. When the water level of the reservoir drops rapidly or remains at the low water level, the transient seepage force impinges along the sliding direction. Due to the hydraulic gradient and the lag of the water level of the rear edge, the deformation of the landslide accelerates. When the water level of the reservoir is slowly decreasing, rising rapidly or at the high level, the landslide is in a relatively stable state. This can be interpreted by the dissipation of pore water pressure, seepage force and the effect of hydrostatic pressure.

Acknowledgments
The authors would like to thank all the participants in this research work. The authors gratefully acknowledge the support provided for this project by the State Key Program of National Natural Science Foundation of China (Grant No. 41427801). The authors also thank the technicians from Suzhou NanZee Sensing Technology Co., Ltd. during the monitoring process.
References

[1] Liu C, Shi B, Shao YX, Tang CS 2013 Experimental and numerical investigation of the effect of the urban heat island on slope stability. Bull Eng Geol Environ, 72 303-310.

[2] Zhang L, Shi B, Zhu H-H. et al 2020 A machine learning method for inclinometer lateral deflection calculation based on distributed strain sensing technology. Bull Eng Geol Environ.

[3] Zhang L, Shi B, Luigi Z, Minardo A, Zhu H-H, Jia L-X 2019 An Fiber Bragg Grating-based monitoring system for slope deformation study in geotechnical centrifuge. Sensors, 19, 1591.

[4] Zhang D, Xu Q, Bezuijen A, Zheng G, Wang HX 2017 Internal deformation monitoring for centrifuge slope model with embedded FBG arrays. Landslides, 14 407-417.

[5] Zhu H-H, Shi B, Yan J-F, Zhang J, Wang J 2015 Investigation of the evolutionary process of a reinforced model slope using a fiber-optic monitoring network. Eng Geol, 186 34-43.

[6] Wang B-J, Li K, Shi, B, Wei G-Q 2009 Test on application of distributed fiber optic sensing technique into soil slope monitoring. Landslides, 6 61-68.

[7] Nither N, Wosniok A, Krebber K, et al 2007 Dike monitoring using fiber sensor-based geosynthetics. ECCOMAS Thematic Conference on Smart Structures and Materials.

[8] Xu D-S, Dong L-J, Borana L, Liu H-B 2017 Early-Warning System With Quasi-Distributed Fiber Optic Sensor Networks and Cloud Computing for Soil Slopes. IEEE Access, 5 25437-25444.

[9] Agrawal R, Imieliński T and Swami A 1993 Mining association rules between sets of items in large database In Proc of the ACM SIGMOD Conference On Management of Data Washington DC: SIGMOD. 1993 207-216.

[10] Bi J-X and Zhang Q-S 2005 Survey of the Algorithms on Association Rule Mining Engineering Science 7 88-94.

[11] Zhang D 2004 BOTDR-based Distributed Optical Fiber Sensing and its Application into Engineering Health Monitoring Nanjing University.

[12] Zhu H-H, Ho A-N-L, Yin J-H, Sun H-W, Pei H-F and Hong, C-Y 2012 An optical fibre monitoring system for evaluating the performance of a soil nailed slope Smart Structures and Systems 9 393-410.

[13] Lin X-S and Guo Y 2001 A study on coupling relation between landslide and rainfall Journal of Catastrophology 16 87-92.

[14] Zhang L, Shi B, Zhang D. et al. 2020 Kinematics, triggers and mechanism of Majiagou landslide based on FBG real-time monitoring. Environ Earth Sci 79, 200.

[15] Zhang L, Shi B, Zhu H-H. et al 2020 PSO-SVM-based deep displacement prediction of Majiagou landslide considering the deformation hysteresis effect. Landslides.

[16] Sun Y-J, Zhang D, Tong H-J and Shi B 2013 Research of distributed fiber optic sensing technology in monitoring of Majiagou landslide of Three Gorges The Chinese Journal of Geological Hazard and Control 24 97-102.