13th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
DOI: 10.3217/978-3-99161-057-1-111

Geo-hazard DFOS Monitoring and its Applications

Bin Shi[1], Honghu Zhu[1], Chengcheng Zhang[1], Mengya Sun[2], Wei Zhang1, Taiyin Zhang[1], Junyi Guo[1]
[1]School of Earth Sciences and Engineering, Nanjing University, No.163 Xianlin Avenue, 210023 Nanjing, China
[2]School of Earth Sciences and Engineering, Hohai University, No. 8 Focheng West Road, 210098 Nanjing, China
email: shibin@nju.edu.cn, zhh@nju.edu.cn, zhang@nju.edu.cn, smy@hhu.edu.cn, wzhang@nju.edu.cn, zhangtaiyin@smail.nju.edu.cn, gjy@smail.nju.edu.cn

ABSTRACT: As the geological body on which humans depend, rock and soil are constantly moving under the action of natural forces and human activities. Their instability often triggers geo-hazards, posing severe threats to the environment, infrastructure safety, and sustainable development. High-quality data acquisition and effective monitoring are essential for geo-hazard prevention and mitigation. The stability of rock and soil is governed by mechanical discontinuous interfaces, which are classified into material, state, and movement interfaces. This paper focuses on distributed fiber-optic sensing (DFOS) technology as an advanced tool for geo-hazard monitoring and early warning. The paper summarizes the authors' achievements over the past two decades in DFOS-based geo-hazard monitoring theory, sensing techniques, and application systems. Key advancements include strain-sensing coupling theory, moisture and seepage monitoring methods, disaster identification and prediction models, and integrated fiber-optic sensing technology platforms. Three representative cases are presented, demonstrating the application of DFOS to monitor the material interface of stope overlying rock, the state interface of land subsidence, and the movement interface of a reservoir slope. Finally, future research directions for fiber-optic sensing in rock-and-soil disaster monitoring are outlined.

KEY WORDS: Rock-and-soil, Interface, Geo-hazard, Monitoring, Distributed fiber-optic sensing (DFOS), Application

1 INTRODUCTION

Earth habitability has become a critical scientific focus in the 21st century, with rock and soil providing the fundamental foundation for human survival and infrastructure development. These geological bodies are constantly subjected to natural forces, such as earthquakes, rainfall, and landslides, as well as anthropogenic disturbances, including excavation, construction, and resource exploitation. Such internal and external forces continuously reshape the physical and mechanical properties of rock and soil, leading to instability that can trigger a variety of geo-hazards. These disasters pose severe threats to the ecological environment, engineering safety, and the sustainable development of society.

The stability and evolution of rock and soil masses are primarily governed by mechanical discontinuity interfaces, which can be categorized into material interfaces, state interfaces, and movement interfaces, as shown in Figure 1. These interfaces play a decisive role in controlling the deformation, failure mechanisms, and overall stability of rock and soil systems under complex external loads. However, their concealed, heterogeneous, and dynamic nature makes real-time monitoring and early identification of potential disaster signals particularly challenging.

Traditional monitoring methods, such as discrete point sensors, geotechnical instrumentation, and geophysical surveys, often suffer from limitations in spatial coverage, resolution, and long-term reliability. These limitations hinder the accurate depiction of internal mechanical evolution and early identification of critical hazard precursors, especially in large-scale and complex geological settings.

To overcome these challenges, distributed fiber-optic sensing (DFOS) technology has emerged as a highly promising tool for in-situ, real-time, and continuous monitoring of geo-hazards [1]. DFOS enables the long-distance, high-resolution, and distributed acquisition of strain, moisture, temperature, and other critical parameters along the entire length of a sensing cable, offering unparalleled advantages in capturing the spatial evolution of mechanical discontinuities and hazard precursors in rock and soil masses.

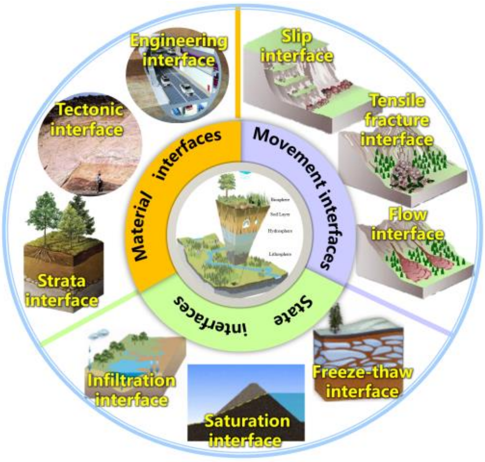


Figure 1 Schematic diagram of rock and soil disasters and the three types of interfaces.

This paper summarizes the key advancements achieved in DFOS-based geo-hazard monitoring by the authors' research group over the past two decades, covering areas such as strain-sensing coupling theory, moisture and seepage monitoring techniques, disaster identification and prediction models, and integrated fiber-optic sensing technology platforms. Furthermore, three representative case studies are presented to demonstrate the practical application of DFOS in monitoring material interfaces, state interfaces, and movement interfaces in

DOI: 10.3217/978-3-99161-057-1-111

complex geotechnical environments, highlighting its unique advantages and future potential in geo-hazard monitoring and early warning.

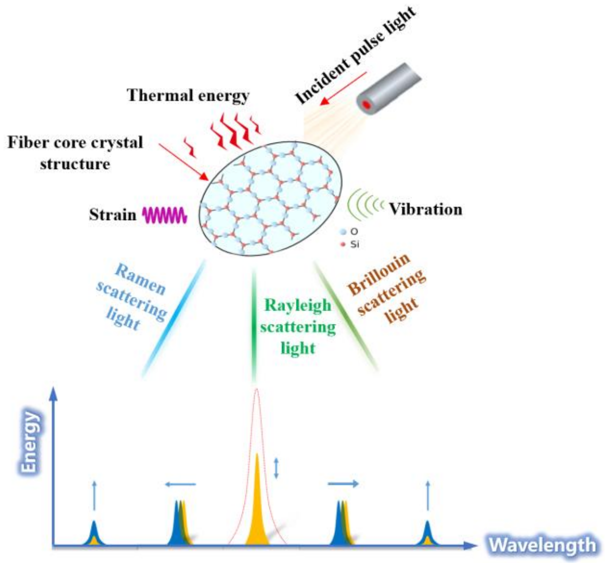
2 DISTRIBUTED FIBER-OPTIC SENSING TECHNOLOGY

DFOS enables continuous spatial and temporal monitoring by utilizing optical fibers as both transmission media and sensing elements. This technology encodes the measured parameter as a function of fiber length, allowing real-time data collection over large areas. By deploying sensing fibers in various configurations, DFOS effectively forms an integrated sensing network within geotechnical structures, providing critical insights into subsurface processes.

DFOS primarily encompasses three key techniques: Distributed Temperature Sensing (DTS) for thermal monitoring, Distributed Strain Sensing (DSS) for strain measurements, and Distributed Acoustic Sensing (DAS) for vibration detection [2], as shown in Figure 2. Additionally, Fiber Bragg Grating (FBG) sensing, including the advanced Ultra-Weak Fiber Bragg Grating (UWFBG) technology, offers high-resolution quasi-distributed measurements.

When embedded within soil and rock formations, DFOS enables real-time monitoring of stress, deformation, temperature, and fluid movement. This capability enhances the early detection of geo-hazards, supports infrastructure health monitoring, and improves disaster prevention strategies. Its ability to provide high-resolution, continuous data makes DFOS an essential tool for geotechnical applications.

(a)



(b)

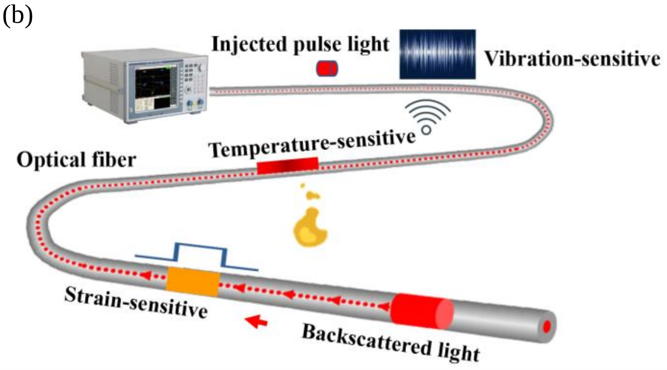


Figure 2 Schematic diagram of the distributed fiber optic sensing technology: (a) Optical principle of 3Ds; (b) 3Ds sensing scheme.

3 FIBER-OPTIC SENSING THEORY AND TECHNOLOGY FOR ROCK-AND-SOIL DISASTERS

The application of fiber-optic sensing technology in rock-and-soil disaster monitoring requires addressing several key theoretical and technical challenges. The primary difficulties lie in understanding and improving the strain coupling mechanism between optical fibers and geotechnical materials, effectively detecting and quantifying moisture infiltration and seepage processes, developing reliable methods for identifying and predicting disaster-related signal events, and constructing an integrated fiber-optic sensing system tailored for geo-hazard monitoring. These challenges must be overcome to enhance the accuracy and reliability of fiber-optic sensing technology in geotechnical applications. The following sections summarize the advancements achieved by the authors' research team in these areas.

3.1 Strain-Sensing Coupling Theory

The strain coupling mechanism between embedded fiber-optic sensors and surrounding geotechnical materials plays a crucial role in ensuring accurate deformation monitoring. Through extensive theoretical and experimental research, the authors have established a progressive failure model for fiber-soil interfaces, revealing the mechanisms governing interfacial bonding strength. On this basis, a criterion for evaluating fiber-soil interfacial adhesion was proposed, alongside a calculation method for determining critical confining pressure and the optimal embedment depth of borehole-installed fibers [3,4]. These findings provide essential guidance for improving fiber installation strategies in geotechnical applications.

To address the challenge of strain transfer in weak soil layers, a novel anchoring approach—fixed-point optical fiber technology—was developed. This technique enhances strain coupling by introducing controlled bonding points along the fiber, preventing signal attenuation due to excessive strain dissipation. By refining strain transfer mechanisms, these advancements have significantly improved the performance of DFOS in complex geological environments, ensuring the accuracy and stability of long-term geotechnical monitoring.

3.2 Moisture and Seepage Sensing Methods

Moisture and seepage are fundamental factors affecting the stability of rock and soil masses. Moisture primarily pertains to unsaturated soils, while seepage involves fluid movement

DOI: 10.3217/978-3-99161-057-1-111

within porous media, often serving as a key trigger for geotechnical failures such as slope instability and land subsidence. Conventional monitoring methods, such as the active heating distributed temperature sensing (DTS) technique proposed by Selker et al., have limitations in accuracy and are only applicable in environments above 0 °C[5]. To overcome these constraints, we introduced the thermal pulse fiber-optic method, which leverages the thermal conductivity variations of geological materials under different moisture and seepage conditions. By integrating optical fibers as active heat sources, this technique enables high-precision, all-weather detection of subsurface moisture and seepage dynamics[6].

To further enhance measurement accuracy, ultra-weak fiber Bragg grating (UWFBG) technology was employed, embedding thousands of ultra-low reflectivity gratings along a single fiber-optic cable. Encapsulated with conductive heating materials, this advancement significantly improved sensing resolution, increasing accuracy from 5% F.S. to 1% and enhancing thermal response sensitivity compared to conventional methods[7]. Once embedded in geological formations, this fiber-optic sensing system enables continuous, high-resolution monitoring of dynamic changes in moisture content, capillary rise, groundwater levels, and seepage velocities. This innovation provides a powerful tool for tracking hydrological processes in unsaturated zones, improving geotechnical disaster prevention strategies, and supporting sustainable groundwater management.

3.3 Geo-hazard Identification and Prediction

Accurately identifying and predicting geo-hazards based on fiber-optic sensing data is essential for early warning and disaster prevention. The Random Forest algorithm, known for its efficiency and strong classification performance, has been applied to develop an intelligent multi-hazard classification system for underground engineering. Field tests in tunnels demonstrated its ability to distinguish construction activities (e.g., excavation, drilling) and sudden disasters (e.g., rockfalls, seepage) with 92.3% accuracy providing a reliable approach to geo-hazard detection [8].

For geo-hazard prediction, the Kalman Filter (KF) is widely used due to its precision and robustness. By integrating multi-physics data from fiber-optic sensors, it enhances anomaly detection accuracy. Since traditional KF models are limited to linear systems, an extended Kalman Filter (EKF) incorporating Taylor series expansion was developed to handle nonlinear geotechnical processes. Genetic algorithm optimization further improved prediction accuracy, enhancing the capability of fiber-optic sensing in forecasting disaster events and supporting proactive risk mitigation [9].

3.4 Fiber-Optic Sensing Technology Systems

Building on advancements in geo-hazard sensing theory and technology, the research team has developed an extensive fiber-optic sensing framework tailored for rock-and-soil disaster monitoring. Over 50 specialized fiber-optic sensing networks have been designed, alongside nearly 10 proprietary signal acquisition devices. Additionally, more than 10 intelligent geo-hazard recognition systems have been established, forming a comprehensive and systematic approach to fiber-optic sensing for geotechnical disaster detection and early warning (Figure 3). This integrated technology system enhances the accuracy, efficiency, and applicability of distributed fiber-optic sensing in diverse geological environments, providing a robust foundation for large-scale geo-hazard monitoring and risk assessment [10,11].

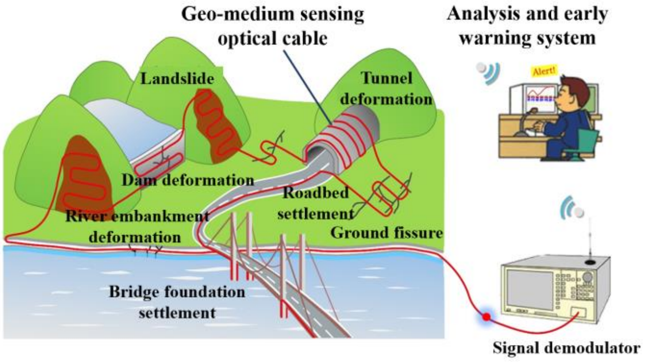


Figure 3 Fiber optic sensing system for rock-and-soil disasters.

4 APPLICATIONS OF DFOS IN ROCK-AND-SOIL DISASTER MONITORING

DFOS has emerged as a transformative technology for monitoring rock-and-soil disaster mechanisms by providing continuous, real-time, and high-resolution data over large spatial extents. Unlike traditional geotechnical monitoring systems that rely on discrete measurement points, DFOS allows for full-scale sensing of deformation, stress redistribution, and hydrological changes that contribute to geotechnical instabilities. This section highlights key applications of DFOS in monitoring material, state, and movement interfaces, with a focus on underground mining operations, land subsidence monitoring, and reservoir slope stability assessment.

4.1 Monitoring Material Interfaces in Stope Overlying Rock

In underground mining operations, the excavation process induces stress redistribution and fracture propagation within the surrounding rock mass. This often leads to instability in stope overburden, posing a significant risk of roof collapse, rock bursts, and ground subsidence. Material interfaces, such as the contact zones between ore bodies and surrounding rock or between different lithological formations, govern the mechanical response of the overlying strata and influence the failure mechanisms within the mine.

DFOS technology has been successfully deployed in longwall mining, sublevel caving, and room-and-pillar mining operations to monitor stress changes and detect potential failure zones [12,13]. Optical fibers installed along critical interfaces allow for real-time strain measurement, enabling the identification of stress concentrations and early warning of geotechnical hazards. By tracking localized deformation trends, strain redistribution, and fracture initiation, DFOS provides mine operators with actionable insights for optimizing roof support systems, adjusting mining sequences, and implementing safety measures to prevent catastrophic failures.

4.2 Assessing State Interfaces in Land Subsidence

Land subsidence is a widespread geo-hazard resulting from excessive groundwater extraction, soil consolidation, and hydro-mechanical interactions. The gradual settlement of soil layers due to subsurface compaction can cause structural

DOI: 10.3217/978-3-99161-057-1-111

damage to buildings, differential ground deformation, and increased flooding risks, particularly in urban areas. State interfaces within subsiding soil formations represent the transition zones between stable and compacting soil layers, where changes in pore pressure, void ratio, and effective stress dictate the rate and extent of subsidence.

DFOS has been increasingly utilized for long-term land subsidence monitoring by embedding fiber-optic sensors in boreholes and along subsiding zones to capture real-time compaction trends. By measuring strain variations, DFOS allows for the early detection of compaction-related deformations, enabling timely intervention to mitigate damage [14]. For example, in cities experiencing significant subsidence due to groundwater depletion, DFOS networks provide high-resolution subsidence maps, allowing urban planners and engineers to develop effective groundwater management policies and infrastructure reinforcement strategies. Additionally, DFOS can be integrated with satellite-based InSAR (Interferometric Synthetic Aperture Radar) data to enhance the accuracy of subsidence monitoring by correlating surface deformation trends with subsurface strain variations.

4.3 Detecting Movement Interfaces in Reservoir Slopes

Reservoir slopes are highly susceptible to landslides and slope failures triggered by hydrodynamic loading, seasonal water level fluctuations, and infiltration-induced weakening of slope materials. Movement interfaces within reservoir slopes define the boundaries between stable and actively deforming soil or rock masses, making them critical zones for monitoring slope stability and identifying potential failure mechanisms.

DFOS-based monitoring has been successfully applied in reservoir embankments, natural slopes, and engineered slopes near hydropower stations to track shear strain accumulation, deep-seated creep deformation, and progressive failure development [15–17]. Fiber-optic sensors embedded along potential slip surfaces and slope reinforcement structures provide continuous measurements of strain evolution, allowing engineers to identify precursory signs of instability before catastrophic failure occurs.

In large-scale reservoir projects such as the Three Gorges Reservoir in China, DFOS has been instrumental in monitoring slope deformation and evaluating landslide risks under varying hydrological conditions [18]. By integrating DFOS data with numerical slope stability models and geotechnical instrumentation, engineers can develop more reliable landslide prediction models, improve early warning systems, and implement targeted mitigation measures, such as slope drainage optimization and reinforcement design [19,20].

5 CONCLUSION

The integration of DFOS technology into geo-hazard monitoring has significantly enhanced the ability to detect, analyze, and mitigate geological and geotechnical disasters. By providing continuous, real-time, and spatially distributed data, DFOS effectively overcomes the limitations of traditional point-based monitoring techniques, enabling more comprehensive and proactive disaster prevention, early warning, and risk assessment. The case studies presented in this paper demonstrate the broad application potential of DFOS technology in underground mining stability evaluation, land subsidence monitoring, and reservoir slope hazard management, highlighting its adaptability to complex geological environments and diverse hazard types.

Future research should focus on further enhancing sensor durability and environmental adaptability, developing more refined data interpretation and inversion models, and integrating DFOS with artificial intelligence (AI), remote sensing, and multi-source data fusion to build intelligent, automated, and predictive hazard monitoring systems. The continuous advancement and interdisciplinary integration of DFOS technology will play a key role in safeguarding geotechnical stability, infrastructure resilience, and sustainable land use under increasingly complex environmental and engineering challenges.

ACKNOWLEDGMENTS

This research was financially supported by the National Natural Science Foundation of China, NSFC (Grant Nos. 42030701, 42177135, 423B2704).

REFERENCES

[1] B. Shi, D. Zhang, H. Zhu, C. Zhang, K. Gu, H. Sang, H. Han, M. Sun, and J. Liu, *DFOS applications to geo-engineering monitoring*, *Photonic Sensors*, vol. 11, pp. 158–186, 2021.

[2] J. Yin, Z. W. Li, Y. Liu, K. Liu, J. S. Chen, T. Xie, S. S. Zhang, Z. Wang, L. X. Jia, C. C. Zhang, and B. Shi, *Toward establishing a multiparameter approach for monitoring pipeline geohazards via accompanying telecommunications dark fiber*, *Optical Fiber Technology*, vol. 68, p. 102765, 2022.

[3] C. C. Zhang, H. H. Zhu, and B. Shi, *Interfacial characterization of soil-embedded optical fiber for ground deformation measurement*, *Smart Materials and Structures*, vol. 23, 2014.

[4] C. C. Zhang, H. H. Zhu, S. P. Liu, and B. Shi, *Quantifying progressive failure of micro-anchored fiber optic cable–sand interface via high-resolution distributed strain sensing*, *Canadian Geotechnical Journal*, vol. 57, pp. 871–881, 2020.

[5] C. Sayde, C. Gregory, M. Gil-Rodriguez, N. Tufillaro, S. Tyler, N. Van De Giesen, M. English, R. Cuenca, and J. S. Selker, *Feasibility of soil moisture monitoring with heated fiber optics*, *Water Resources Research*, vol. 46, 2010.

[6] M. Y. Sun, B. Shi, C. Zhang, J. Liu, J. Guo, X. Zheng, Y. Wang, and G. Wei, *Quantifying the spatio-temporal variability of total water content in seasonally frozen soil using actively heated fiber Bragg grating sensing*, *Journal of Hydrology*, vol. 606, p. 127386, 2022.

[7] X. Ye, H. H. Zhu, J. Wang, Q. Zhang, B. Shi, L. Schenato, and A. Pasuto, *Subsurface multi-physical monitoring of a reservoir landslide with the fiber-optic nerve system*, *Geophysical Research Letters*, vol. 49, 2022.

[8] T. Y. Zhang, B. Shi, C. C. Zhang, T. Xie, and J. Yin, *Tunnel disturbance events monitoring and recognition with distributed acoustic sensing (DAS)*, *IOP Conference Series: Earth and Environmental Science*, vol. 861, 2021.

[9] K. Liao, W. Zhang, H. H. Zhu, Q. Zhang, B. Shi, J. T. Wang, and W. T. Xu, *Forecasting reservoir-induced landslide deformation using genetic algorithm enhanced multivariate Taylor series Kalman filter*, *Bulletin of Engineering Geology and the Environment*, vol. 81, pp. 1–19, 2022.

[10] S. P. Liu, B. Shi, K. Gu, C. C. Zhang, J. H. He, J. H. Wu, and G. Q. Wei, Fiber-optic wireless sensor network using ultra-weak fiber Bragg gratings for vertical subsurface deformation monitoring, Natural Hazards, vol. 109, pp. 2557–2573, 2021.

[11] H. Sang, D. Zhang, Y. Gao, L. Zhang, G. Wang, B. Shi, B. Zheng, and Y. Liu, Strain distribution based geometric models for characterizing the deformation of a sliding zone, Engineering Geology, vol. 263, p. 105300, 2019.

[12] G. Cheng, B. Shi, H. H. Zhu, C. C. Zhang, and J. H. Wu, *A field study on distributed fiber optic deformation monitoring of overlying strata during coal mining*, *Journal of Civil Structural Health Monitoring*, vol. 5, pp. 553–562, 2015.

[13] G. Cheng, W. Xu, B. Shi, J. Wu, B. Sun, and H. Zhu, *Experimental study on the deformation and failure mechanism of overburden rock during coal mining using a comprehensive intelligent sensing method*, *Journal*

DOI: 10.3217/978-3-99161-057-1-111

of Rock Mechanics and Geotechnical Engineering, vol. 14, pp. 1626–1641, 2022.

[14] C. Liu, B. Shi, K. Gu, T. Zhang, C. Tang, Y. Wang, and S. Liu, *Negative pore water pressure in aquitard enhances land subsidence: Field, laboratory, and numerical evidence*, *Water Resources Research*, vol. 58, 2022.

[15] Y. J. Sun, D. Zhang, B. Shi, H. J. Tong, G. Q. Wei, and X. Wang, *Distributed acquisition, characterization and process analysis of multi-field information in slopes*, *Engineering Geology*, vol. 182, pp. 49–62, 2014.

[16] H. H. Zhu, B. Shi, J. F. Yan, J. Zhang, and J. Wang, *Investigation of the evolutionary process of a reinforced model slope using a fiber-optic monitoring network*, *Engineering Geology*, vol. 186, pp. 34–43, 2015.

[17] H. H. Zhu, B. Shi, J. F. Yan, J. Zhang, C. C. Zhang, and B. J. Wang, *Fiber Bragg grating-based performance monitoring of a slope model subjected to seepage*, *Smart Materials and Structures*, vol. 23, 2014.

[18] X. Ye, H. H. Zhu, G. Cheng, H. F. Pei, B. Shi, L. Schenato, and A. Pasuto, *Thermo-hydro-poro-mechanical responses of a reservoir-induced landslide tracked by high-resolution fiber optic sensing nerves*, *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 16, no. 3, pp. 1018–1032, 2024.

[19] C. C. Zhang, H. H. Zhu, S. P. Liu, B. Shi, and D. Zhang, *A kinematic method for calculating shear displacements of landslides using distributed fiber optic strain measurements*, *Engineering Geology*, vol. 234, pp. 83–96, 2018.

[20] W. Zhang, R. Xiao, B. Shi, H. H. Zhu, and Y. J. Sun, *Forecasting slope deformation field using correlated grey model updated with time correction factor and background value optimization*, *Engineering Geology*, vol. 260, p. 105215, 2019.