
Theory and Engineering Applications of Intelligent Deformation Monitoring and Prediction for Deep Subway Excavations

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SGIDI Engineering Consulting (Group) Co., Ltd.

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FOREWORD

The rapid and sustained advancement of urbanization has increasingly rendered the development of underground space a crucial and, in many contexts, an inevitable strategy for alleviating urban traffic congestion and addressing the growing scarcity of land resources. Metro engineering, particularly deep excavation construction, poses exceptionally severe challenges to safety monitoring and risk early warning due to its inherently large scale, complex and uncertain environmental conditions, and elevated risk profiles. When confronted with monitoring data that are high-frequency, multi-source, heterogeneous, and fundamentally nonlinear, traditional monitoring approaches and conventional prediction theories have gradually and clearly revealed their significant limitations.

Entitled “Theory and Engineering Applications of Intelligent Deformation Monitoring and Prediction for Deep Subway Excavations”, this book aims to systematically establish and elaborate a high-frequency intelligent monitoring system that encompasses multiple physical quantities and multiple scales, together with a rigorous nonlinear time-series prediction theory. The research work and achievements presented herein are primarily based on sustained theoretical explorations, dedicated equipment development, and extensive engineering verifications conducted by the author and the research team over the past several years, relying on a series of metro deep excavation projects (e.g., Shaoxing Metro Line 2 and Wuxi Metro Line 4).

The book elaborates in considerable detail on the underlying principles, system configurations, and practical engineering applications of a suite of intelligent monitoring methods. These methods include multi-channel strut axial force sensing, integrated water level gauges, fixed inclinometers, hydrostatic leveling, terrestrial laser scanning, and multi-mode multi-frequency Global Navigation Satellite System (GNSS). Furthermore, it provides an in-depth investigation into the progressive evolution of prediction theories, tracing a clear trajectory from the classical Autoregressive Integrated Moving Average (ARIMA) model to advanced deep learning models—such as the Gated Recurrent Unit (GRU), Long Short-Term Memory (LSTM), and Bidirectional Long Short-Term Memory (BiLSTM)—and ultimately to the Spatiotemporal Mamba (ST-Mamba) model, which seamlessly integrates both spatial and temporal features to achieve superior predictive performance.

The chapters of this book are designed to be relatively independent in their thematic focus while remaining tightly interrelated and mutually reinforcing. Collectively, they form a complete and coherent technical closed loop that extends from “intelligent perception” at the data acquisition stage to “scientific prediction” at the decision-making stage. It is sincerely hoped that the

publication of this book will offer valuable theoretical reference and practical technical insights for scholars, engineers, and practitioners dedicated to the field of underground engineering safety, and will jointly promote the continuous advancement of metro construction toward a paradigm that is demonstrably safer, smarter, and more efficient.

LIST OF ABBREVIATIONS

- ADOP: Ambiguity Dilution of Precision
- API: Application Programming Interface
- ARIMA: Autoregressive Integrated Moving Average
- AttnGCN: Attentive Graph Convolutional Network
- BIM: Building Information Modeling
- BDS: BeiDou Navigation Satellite System
- BiLSTM: Bidirectional Long Short-Term Memory
- CBOC: Composite Binary Offset Carrier
- CDMA: Code Division Multiple Access
- CNN: Convolutional Neural Network
- ConvLSTM2D: Convolutional LSTM 2D
- DD: Double-Differenced
- DEM: Digital Elevation Model
- DOY: Day of Year
- DTU: Data Transfer Unit
- ENU: East-North-Up
- EWL: Extra-Wide-Lane
- FDMA: Frequency Division Multiple Access
- FOC: Full Operational Capability
- GALILEO: European Global Navigation Satellite System
- GCN: Graph Convolutional Network
- GEO: Geostationary Orbit
- GLONASS: Global Navigation Satellite System (Russia)
- GNSS: Global Navigation Satellite System
- GPS: Global Positioning System
- GRU: Gated Recurrent Unit
- GST: Galileo System Time
- HDR: High Dynamic Range
- ICP: Iterative Closest Point
- IF: Ionosphere-Free
- IGSO: Inclined Geosynchronous Orbit
- IOV: In-Orbit Validation

- IoT: Internet of Things
- IP: Ingress Protection
- ITU: International Telecommunication Union
- LAMBDA: Least-squares AMBiguity Decorrelation Adjustment
- LCD: Liquid Crystal Display
- LTE: Long Term Evolution
- LSTM: Long Short-Term Memory
- MEMS: Micro-Electro-Mechanical System
- MEO: Medium Earth Orbit
- MMM: Multi-Mode Multi-Frequency
- MQTT: Message Queuing Telemetry Transport
- NB-IoT: Narrowband Internet of Things
- OS: Open Service
- PAR: Partial Ambiguity Resolution
- PDOP: Position Dilution of Precision
- PPP: Precise Point Positioning
- PRS: Public Regulated Service
- QZSS: Quasi-Zenith Satellite System
- RMSE: Root Mean Square Error
- RTK: Real-Time Kinematic
- SAR: Search and Rescue
- SLAM: Simultaneous Localization and Mapping
- SMS: Short Message Service
- SNR: Signal-to-Noise Ratio
- SoL: Safety of Life
- ST-Mamba: Spatiotemporal Mamba
- TLS: Terrestrial Laser Scanning
- TMBOC: Time-Multiplexed Binary Offset Carrier
- UTC: Coordinated Universal Time
- VA: Vertical Accuracy
- WLAN: Wireless Local Area Networks
- WL: Wide-Lane

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Introduction

1.1 Background and Significance

Metro engineering constitutes a critical category of infrastructure that significantly alleviates urban traffic pressure, conserves scarce land resources, and fosters environmentally sustainable green mobility. As of August 2021, a total of 247 urban rail transit lines had been put into operation across China, spanning a cumulative operating mileage of 7,970 kilometers, with a substantial number of additional lines still under active construction. Constrained by the intense scarcity of underground space in urban environments, metro stations and running tunnels are frequently constructed using the deep excavation method. Deep excavation engineering involves a series of closely coupled and highly complex procedures, including earth excavation, dewatering, installation and staging of support systems, and soil improvement. The construction-induced disturbances can markedly alter the in-situ stress field and seepage field of the surrounding soils, thereby triggering a spectrum of risks such as deformation of the retaining structures, variations in the internal forces within the support system, fluctuations in the groundwater table, and ground surface settlement in the vicinity. Consequently, conducting systematic, reliable, and high-precision deformation monitoring together with scientifically rigorous prediction represents the core technical approach for ensuring construction safety and controlling the environmental impacts.

The objects of deformation monitoring for deep excavations can be broadly classified into two major categories: the supporting–retaining system itself and the adjacent environment. Monitoring of the supporting–retaining system primarily encompasses the axial forces in steel struts and/or reinforced concrete struts, deep horizontal displacement of the retaining structures, groundwater levels, and the settlement and horizontal displacement at the top of the retaining structures. Monitoring of the adjacent environment mainly includes ground surface settlement around the excavation, and deformation of nearby buildings, structures, and utility pipelines. Traditional monitoring methods largely rely on manual geometric leveling, total stations, portable inclinometers, and electric water level gauges. Although these approaches can achieve relatively high accuracy under certain specific conditions, they generally suffer from a set of pronounced drawbacks: high labor intensity, low monitoring frequency, poor data continuity, difficulty in

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大湾区规划 · Introduction

《粤港澳大湾区发展规划纲要》明确了澳门“一个中心、一个平台、一个基地”的三个定位，即：建设世界旅游休闲中心、中国与葡语国家商贸合作服务平台，**打造以中华文化为主流、多元文化共存的交流合作基地。**

It further clarified the three orientations of "one center, one platform and one base" of Macao, namely, to build a world tourism and leisure center, a business and trade cooperation service platform between China and Portuguese-speaking countries, and to build an exchange and cooperation base with Chinese culture as the mainstream and multicultural coexistence.

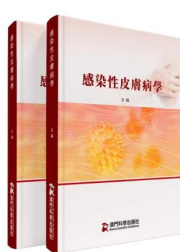


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- 內分泌系統疾病 Endocrine system disease



- 實用小兒內科學 Practical pediatric internal medicine
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