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Preface

During the operation of the subway, the vibration caused by the subway cyclic loading exists for a long time, which will reduce the strength of the soft soil foundation, generate different degrees of settlement and deformation, affect the deformation of the tunnel axis, and cause ground subsidence. The traffic facilities of many subway construction projects are usually built on soft soil foundation. In the initial stage of operation after the construction of freezing method, due to the action of cyclic loading, consolidation deformation settlement often occurs, which has great safety problems.

Supported by the Fundamental Research Funds for the Central Universities (Grant No. 2018ZZCX04) and the National Key Research and Development Program (Grant No. 2017YFC1500702), this monograph studies the dynamic characteristics of soil around subway shield tunnel by artificial freezing method, which can provide theoretical basis and guidance for the effective control of long-term subway settlement and maintaining the safety of subway operation.

Chapter 1 is Introduction. It introduces the progresses of the mechanical properties of soft clay under cyclic loading, the physical and mechanical properties of soft clay under freeze-thaw cycle and the macroscopic and microstructural characteristics of soft clay.

Chapter 2 is Artificial freezing for by-pass of subway tunnel. In this chapter, the artificial freezing method used in the construction of the by-pass in the silty clay stratum is introduced. The design of freezing parameters, construction technologies, monitoring of the temperature field and deformation are introduced systematically.

Chapter 3 is Axial strain of silty clay before and after freezing and thawing. In this chapter, a series of cyclic triaxial tests have been carried out to investigate the dynamic behavior of soft clays before and after freezing-thawing. The stress-strain backbone loop, axial strain and excess pore pressure of the grey muck clay are evaluated and compared under different frequencies and cyclic stress ratios.

Chapter 4 is Freezing-thawing on dynamic characteristics of silty clay. In this chapter, 12 cyclic triaxial tests have been carried out to investigate the dynamic characteristics of the silty clay before and after freezing-thawing, including the dynamic modulus, the damping ratio, the dynamic strain and the excess pore water pressure, etc.

Chapter 5 is Microscopic pore structures of silty clay before and after freezing-thawing by SEM. The parameters of microscopic pore structure of the silty clay, including the pore shape coefficient, the pore orientation anisotropy, the pore size distribution and the fractal dimension, are evaluated with different frequencies, cyclic stress ratios and freezing temperatures.

Chapter 6 is Microscopic pore structures of silty clay before and after freezing-thawing by MIP. In this chapter, 14 MIP tests following the cyclic triaxial tests of the silty clay of layer No. 5 in Shanghai were conducted to investigate the variation of the PSD of the silty clay. The effects of freezing-thawing and cyclic loadings on the PSD of the silty clay were evaluated and the MIP derived water retention curves of the silty clay were predicted with the van Genuchten model.

Chapter 7 is Dynamics of silty clay around subway shield tunnel before and after freezing and thawing by numerical simulation. In this chapter, the three-dimensional governing equations were derived and the solving method was given. The material parameters of the thawing soil and the undisturbed soil used in the numerical simulations were obtained by dynamic triaxial tests. The dynamic response of thawing soil and undisturbed soil in the same environmental conditions were compared and analyzed.

Chapter 8 is Conclusions and Prospects. This part comprehensively summarizes the research conclusions. Several controversial issues are discussed and then the further research work and prospects are simply described.

This monograph has been prepared with the combined effort of all researchers in the group under Prof. Zhen-Dong Cui's leading, in which Zhong-Liang Zhang, Zhi-Xiang Zhan, Chen-Yu Hou, Yan-Kun Zhang and some other students all have involved in this comprehensive research work in this monograph.

Xuzhou, People's Republic of China Prof. Zhen-Dong Cui
February 2020

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About the Author

Prof. Dr. Zhen-Dong Cui is the Dean of Institute of Geotechnical Engineering, China University of Mining and Technology. In July 2008, he obtained Ph.D. from School of Civil Engineering, Tongji University, Shanghai, China. Since then, he had been a postdoctoral research fellow in the Hong Kong University of Science and Technology for one year. He joined Shanghai Institute of Geological Survey in 2009. In July 2010, he joined CUMT as an associate professor and was promoted to full professor in 2013. Supported by China Scholarship Council, from Aug. 2015 to Aug. 2016, as a visiting scholar, he researched and studied in the Department of Civil, Environmental and Architectural Engineering, University of Colorado Boulder.

He won Nomination of 100 Excellent Doctoral Dissertations in China in 2011. He won Shanghai Excellent Doctoral Dissertations in 2010 and Excellent doctorate thesis of Tongji University in 2009. In 2015, he was awarded the third prize of Shanghai Natural Science. In 2013, he was awarded the second prize of Natural Science of the Ministry of Education. In 2008, he was awarded the second prize of Progress of Science and Technology in Shanghai. In 2012, he was selected as Qinglan Project for Outstanding Young Teachers of Jiangsu Province and in 2016, he was selected as 333 Talent Project in Jiangsu Province. In 2014 and in 2017, he was twice selected as Young Academic Leader of

China University of Mining and Technology. In 2015, he was awarded as Excellent Innovation Team Leader of China University of Mining and Technology.

His research interests focus mainly on the urban subway tunnel, the deformation of soft foundation, the soil dynamics, the centrifuge model test and the artificial frozen soil. In the past 5 years, he took charge of National Natural Science Foundation of China (NSFC), Jiangsu Natural Science Foundation of China, Outstanding Innovation Team Project in China University of Mining and Technology and Special Fund for China Postdoctoral Science Foundation. He published more than 60 papers, in which 38 English papers (indexed by SCI) have been published in Engineering Geology, Natural Hazards, Computers and Geotechnics, Cold Regions Science and Technology, Environmental Earth Sciences, International Journal of Rock Mechanics and Mining Sciences, etc. He has applied for 10 national invented patents, among which five patents have been awarded. He is the specialized committee member of the soft soil engineering of the geotechnical engineering branch of the Civil Engineering Society of China, the member of International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) and the member of International Association for Engineering Geology and Environment (IAEG).

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Chapter 1
Introduction

1.1 Background

On January 13, 1863, the first underground railway system in the world—London Metropolitan Railway, was opened to traffic in London. The rapid development of the underground railway has brought urban transportation into the era of rail transit. At present, more than 300 subway lines have been opened in more than 100 cities around the world, with a total length of more than 7000 km, which makes the subway an important symbol of the economic development of a city. With the rapid development of economy and technology in China, the traffic pressure brought by the process of urbanization is very huge. Therefore, the construction of the underground railway is the most effective way to solve this problem. There are also many issues that need to be researched for geotechnical underground engineering.

Soft clay is widely distributed in China, especially in the southeast coastal areas. Since the end of the last century, with the rapid development of urban engineering construction in Shanghai, many large-scale transportation facilities and projects have been built on soft soil foundation. The bearing capacity of soft clay foundation is low, the strength increases slowly, and it has the characteristics of low permeability, high rheology, high water content and high compressibility, so its engineering properties are poor (Huang 1983). The problems such as urban ground subsidence caused by the mechanical properties of soft clay, excessive stratum deformation and instability of deep foundation pit excavation have become increasingly prominent.

After more than half a century of development, the subway construction methods in China have developed rapidly. At the beginning, the open cut method is mainly used, and now the surface excavation method, drilling and blasting method and shield method are adopted. No matter which construction method it is, the subway will inevitably produce vibration and settlement in the process of construction and operation, as well as the impact on the surrounding environment (Wang et al. 2003).

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Because of the advantages of small ground influence, fast progress and strong adaptability of geological conditions, shield method has been adopted in most subway construction projects in China, and has become the most advanced subway construction technology at present. In some complicated construction environments, especially in the southeast coastal areas, the conventional construction methods sometimes cannot maintain the stability of the soil around the tunnel, it is necessary to adopt some special construction methods, among which the freezing method is widely used because of its high strength, good controllability and strong applicability. In the process of freezing construction, the volume of pore water in the soil will change when it freezes, which increases the pore volume in the soil, leads to the expansion of the soil, the instability of the mechanical properties and the uneven surface deformation. And the soil is soft and easily deformed after thawing, producing greater uneven settlement. The effect of frost heaving and thaw collapsing is also the main problem of freezing method in the construction of subway tunnel (Yu et al. 2005).

During the operation of the subway, the vibration caused by the subway cyclic loading exists for a long time, which will reduce the strength of the soft soil foundation, generate different degrees of settlement and deformation, affect the deformation of the tunnel axis, and cause ground subsidence (Huang et al. 2006; Chen et al. 2005; Jiang 2002; Liu et al. 2004; Zhao 2006). The traffic facilities of many subway construction projects are usually built on soft soil foundation. In the initial stage of operation after the construction of freezing method, due to the action of cyclic loading, consolidation deformation settlement often occurs, which has great safety problems.

The settlement of a Japanese railway reached nearly 1 m in the five years after it was put into operation. There was almost no settlement on Shanghai Metro Line 1 before it was completed and opened to traffic, but its settlement reached 40–60 mm in eight months after operation. These examples indicate that soft clay will have large deformation and settlement under cyclic loading. If uneven settlement cannot be effectively controlled, it will cause tunnel leakage, segment fracture, building tilt or collapse, foundation instability and more serious land subsidence disasters.

Therefore, it is of great significance to study the dynamic characteristics of soil around subway shield tunnel by artificial freezing method, which can provide theoretical basis and guidance for the effective control of long-term subway settlement and maintaining the safety of subway operation.

1.2 Mechanical Properties of Soft Clay Under Cyclic Loading

Under cyclic loading, there are many factors affecting the dynamic characteristics of soft clay, including soil properties, loading frequency, cyclic stress ratio, vibration times, stress history, consolidation method, and drainage conditions. By using of indoor cyclic triaxial test, resonant column test, dynamic load test and computer