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Foreword

Rapid development of the Chinese economy has spurred and accelerated major urbanization construction. With lots of people migrating into large and medium cities, the previous existing urban transportation hardly meets the demand of the population expansion and urban sprawl. Establishing spacing transportation network is the key to alleviate the situation of traffic congestion, in which subway plays a significant role to develop the traffic underground space without any large disturbance to the surface construction. Subway systems bring free-flow traffic at all times and realize multidimensional space traffic to make faster modernization of urban development.

In China, since the first subway showed up in Beijing in the 1960s, Shanghai, Guangzhou, Shenzhen, Nanjing and Tianjin all followed and interlaced the heartland by subways. Currently more than 20 cities have also planned or already opened subway construction to traffic such as Wuhan, Zhengzhou, Changsha, Suzhou, and Ningbo. Particularly, in Beijing, Shanghai, and Guangzhou, in these three big cities, subway systems all develop so well that about 200–400 km subway line has been established to form a really huge traffic hub, which promote the urban development greatly.

Subway construction is really helpful for solving urban traffic problems, but a number of issues also should be paid much attention especially in coastal cities with large area of soft soil located. In poor geological conditions, the study for subway design and construction is essential to prevent and reduce the occurrence of accidents. Meantime, there is no specific and detailed study before the subway system started construction. It is much lack of long-time experiments and monitoring during the fast construction of underground traffic space. Hence, without thorough understanding of geological conditions and practice experiences, several hidden problems and issues would be resulted in many aspects.

This monograph has been prepared with the combined effort of all researchers in the group under Prof. Tang's leading. It is the greatest achievement on several years' research accumulation. Lots of results about subway construction were figured out by authors especially in soft soil area. It is very valuable research results from the

practice experiences of Shanghai Subway Lines 1 and 2 and also some kind of exploratory study for the subway construction in Shanghai or other soft soil areas.

In recognition of the importance of improving and expanding the theoretical base to provide reference for subway design and construction, Prof. Tang has been conducting comprehensive research supported by the National Natural Science Foundation of China (Grant No. 40372124 and No. 41072204) and Shanghai Post-doctoral Foundation. The dynamic response characteristics of soft clay surrounding tunnel under subway vibration load are studied in this research project. The main content is characterized as follows:

1. From a specific view, the soil structure was selected as a start point of research in depth. Through field monitoring and laboratory experiments, large numbers of data were provided as analysis basis to the potential effects. Considering advantages and disadvantages in subway construction, interior characteristics of soil structure, bearing capacity, and compressibility and settlement problems were all analyzed.
2. The soil deformation and dynamic response effect were discussed along with the intrinsic properties of soil with the vibration load. It includes the soil response frequency to subway vibration load, soil dynamic characteristics under high-frequency and low frequency load.
3. The concept of multi-methodology of geological monitoring and various testing and vibration experiments is presented in this book. Numerous data were summarized and were mutually proven by each other to establish relevant mathematical model. It can be suitable for field analyzing and also has significant application.
4. The engineering effect on surrounding environment and buildings was discussed based on the long-term subway foundation, soil characteristics, and the vibration load state. Some valuable prediction information can be provided.

The research results in this monograph have great practice value to guide the subway design and construction projects, particularly for effectively controlling and alleviating or even preventing the land subsidence effects caused by large area subway vibration load. Being so systematic and practical, this monograph is unique and outstanding on subway construction since the subway system developed in large scale in the 1990s in Shanghai. It's really hard to find another similar one even all over China. I am pretty sure that once this monograph is published, it must be a great reference and have a significant guide on underground space network traffic construction in Shanghai, Eastern China, and all the southern soft soil areas.

Chinese Academy of Engineering
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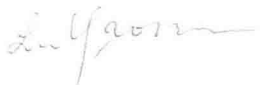

Academician Yaoru Lu

Preface

Rapid development of the Chinese economy has spurred and accelerated major urbanization construction. Traffic problems emerge gradually. Establishing spacing transportation network is the key to alleviate the situations of large population, dense buildings, narrow streets, and traffic congestion. Subway system is paid more attentions due to its advantages of high speed, safety and comfortability. Most importantly, it develops the traffic underground space without any large disturbance to the surface construction. Currently, subway lines are constructed in Shanghai, Beijing, Tianjin, Shenzhen, Ningbo, and Chongqing to mitigate the traffic loads. Even some small cities are applying for subway construction now. As for Shanghai, there are already 400 km lines in total in the rail transit system. Further planning to 2020, there will be 21 lines in Shanghai Metro, which is 840 km in total. However, at the same time, this sharp development of subway systems has brought in lots of environmental problems as well. Particularly, large deformation arises in the surrounding soil near subway tunnel and the foundation. Ground subsidence influences the surrounding environment.

Supported by the National Natural Science Foundation of China (Grant No. 40372124 and No. 41072204), National Specialty Comprehensive Reform Pilot Project (the project number: higher educational letter [2013] No. 2), National Key Technologies R&D Program of China (Grant No. 2012BAJ11B04), and Shanghai Postdoctoral Foundation, this monograph comprehensively presents the research on the dynamic response characteristics of saturated soft clay surrounding the subway tunnel under the subway vibration loads. Most subway lines in Shanghai were or are being designated in the saturated soft clay layer, which is characterized by high void ratio, large natural water content, poor permeability, high compressibility and low shear strength, etc. Under long-term subway vibration loading, the saturated soft clay may gradually be compressed and residual deformation will result in deflection of tunnel axis, land subsidence, and even tilt or collapse of surrounding buildings. To prevent such disasters, the dynamic properties, deformation mechanism, and settlement characteristics should be figured out under vibration loading. Aimed at this, during the research process, field sampling, monitoring, and laboratory experiments are combined; elastoplastic theory, material mechanics, fracture mechanics, and

nonlinear dynamic mechanics are employed as the basis; dynamic triaxial system (GDS), scanning electron microscopy (SEM), and mercury intrusion porosimetry (MIP) apparatus are utilized to simulate the soil dynamic properties. Through all the above, the microstructure deformation and failure mechanism are analyzed; meanwhile, the long-term settlement and land subsidence characteristics are simulated by finite element method (FEM); an applicable prediction model is proposed. Some valuable conclusions are drawn finally.

Chapter 1 is Introduction. It summarizes the recent researches and progresses all over the world of the study on five areas including soil structure, the dynamic response to subway vibration loads, the dynamic properties of soft clay under vibration loads, microstructure of soft clay, and the long-term settlement of soft foundation under vibration loads. Hereby it points out the purpose and research strategy in this monograph.

Chapter 2 is Field Tests. All the tests were conducted around the site of Jing'an Temple Station in Line 2, Shanghai Metro. There were 5 boreholes drilled along and perpendicular to the tunnel axis. Earth pressure and pore water pressure transducers were placed in different distances away from the tunnel edge along and vertically at various depths. The developments of earth pressure and pore water pressure under subway vibration loads were monitored in real time. Processing the field data, it was found that the frequency of soft clay responding to train operation can be divided into two parts: high frequency (2.4–2.6 Hz) and low frequency (0.4–0.6 Hz). The attenuation relationship of the dynamic response along the distance in the vertical line of the tunnel axis is also derived. Through this formula, the impact scope and the dynamic response values can be calculated, and the influence of vibrated subway loading on the surrounding buildings can be evaluated and predicted. All these can provide theoretical reference for the design and construction of the buildings around subway.

Chapter 3 is the Laboratory Tests. With the data of field monitoring, by means of laboratory tests of CKC, GDS (Global Digital Systems), SEM (scanning electron microscopy), and MIP (mercury intrusion porosimetry), the further study on the variation of pore water pressure, soil strength, dynamic constitutive relation, and dynamic elastic modulus under different vibration frequencies and vibration cycle numbers are presented. In addition, the microstructure deformation and damage mechanism are also discussed. It is resulted that the increase of pore water pressure is divided into three stages. They are rapid growth stage, slow growth stage, and stable stage. Logistic model is fitted for the variation of pore water pressure, in which the correlation coefficient reaches above 0.99. During the rapid growth stage, the velocity of increase on pore water pressure is not a stable value. The pore water pressure curve is a sharp dip line during the initial short time and then gets into slow decaying. Through regression analysis, the variation of pore water pressure is much consistent with the ExpDecay2 model line. In addition, after the cessation of the vibrated subway loading applied, the pore water pressure sharply declines and then gets into a stable value a little above the hydrostatic pressure. Secondly, the deformation of saturated soft clay soil under the cyclic subway loading is much related to the cyclic stress ratio, confining pressure, vibration frequency, and number

of vibration. There exists a threshold cyclic stress ratio value during the vibrated loading, which is associated with the properties of soil, the vibrated loading, the confined value, etc. When the vibrated loading applied is smaller than the value under the threshold cyclic stress ratio, with the increasing of the cyclic number, the deformation of soil gets larger but the rate declines and the amplitude of vibration gradually reduces till to a constant. Vice versa, as the cyclic number is growing, the deformation breaks out quickly and is ultimately destroyed. While the axial deformation in the bottom of subway tunnel lasts a very short rebound phase then immediately gets into the plastic deformation stage and large axial deformation occurs. Hence, even though large deformation will not take place in the surrounding soil at a long time in the subway operation, the differential settlement may generate as time goes on.

Chapter 4 is the Research of Microstructure. By means of the advanced microtesting methods of SEM (scanning electron microscopy) and MIP (mercury intrusion porosimetry), the variation of microstructure of the saturated soft clay soil under the vibrated subway loading is discussed from qualitative and quantitative point combined. Meanwhile, the deformation mechanism is analyzed in microstructure aspect through the test results. With the automatic mercury intrusion porosimetry, the samples before and after vibration are quantitatively analyzed in pore size distribution, quantity, and other parameters of pore structure. Supplemented by SEM images in the qualitative analysis, the contact of microstructure and the corresponding macroscopic mechanical properties are established. The results show that there is mainly flocculation, cellular-flocculation structure, in the saturated soft clay. The clay minerals are mostly illite with some chlorite, montmorillonite, etc. Structure unit is generally in the shape of thin sheet. The aggregates are flocculent and feathery. The contact status of the structure units appears in the mode of side-surface or side-side, which is resulted in the aerial structure of the muddy clay with high void ratio. The pore size is distributed mainly in the large pore, and the ink-bottle effect shows up during the process of mercury intrusion. When the depth deepens, the cyclic stress ratio increases, and the total specific surface area of pores firstly declines and then rebounds slightly; the uniform pore size, mercury-retention coefficient, and porosity all increase and then slightly reduce. In addition, it is detected that the Masonry Model is not suitable for the explanation of the deformation mechanism of the saturated soft clay under low stress condition. The fractal theory is confirmed to analyze the pore size distribution. When using different fractal models, the description on the pore size distribution sometimes has a little difference. In this book, the fractal results in thermodynamic relation is much better than that in Menger model as for saturated soft clay.

Chapter 5 is the Finite Element Modeling. According to the field monitoring data, three-dimensional finite element computer model is established to simulate the dynamic response of the surrounding soil when the subway passes by. The further long-term land subsidence is also obtained in the subway operation.

Chapter 6 is the Settlement Prediction of Soils Surrounding Subway Tunnel. By means of Newton's quadratic interpolation polynomial method, non-isochronous data sequence is converted to isochronous data sequence. The GM (N, 1) model of

non-isochronous data sequence is established. This advantage of using this method is that the impact factors are not simply superposed. Based on the field monitoring data, comparatively analyzing the settlement data, the results show that GM (2, 1) and GM (1, 1) have the higher accuracy. It is much more suitable for the sample volume larger than 4, and the prediction value is much closer to the real settlement. Analyzing the field monitoring data, the rate of settlement in the first half year is obviously lower than that in the second half year.

Chapter 7 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. Yiqun Tang's leading, in which Prof. Nianqing Zhou, associate Prof. Ping Yang, Doctor Xi Zhang, Ph.D. student Jie Zhou, Xingwei Ren, and some other master students all have involved in this comprehensive research work in this monograph. Especially, the writing and finalized editing are conducted by Prof. Tang, graduate student Jie Zhou, and Qi Yang. Xingwei Ren, Jun Li, and Qi Yang are also involved in the information processing and interpretation work.

Though this monograph has been published out on our researches, it is just the first step in our research work. A lot of relevant problems are still needed to explore. All the authors hope this monograph can bring in many more researchers' interests to get involved in this area.

Tongji University
Shanghai, People's Republic of China
June 2013

Prof. Yiqun Tang

Brief Introduction for the Book

This book is written based on the research project "Micro-structure Changes and Dynamic Characteristics of Saturated Soft Clay Around the Subway Tunnels Under Train Loading" which is mainly supported by Natural Science Foundation of China (Grant No. 40372124 and No. 41072204). The primary study object of this book is the dynamic loading induced by subway trains and dynamic responses of the soft clay around tunnels. Microscopic and macroscopic methods were applied in the experimental study and theoretical analysis. Field test was conducted to study the characteristics of the dynamic load induced by the subway train; it was also applied to obtain the distribution law of the dynamic stress in the soft clay around the tunnel. According to the analysis of the field monitoring data, a series of laboratory tests were conducted to study the dynamic response of the soft clay under different dynamic loading (frequency, amplitude, and loading times). Meanwhile, we conducted corresponding microscopic tests for further understanding of the deformation mechanism of soft clay under dynamic loading. Through all the above tests, the dynamic strain–stress relationship, the generation and dissipation of excess pore water pressure, and the changes of the microstructure were discussed in the book. This book also discussed the ground settlement induced by subway train loading, and its long-term prediction was studied as well. The conclusions obtained from this study are meaningful to the theoretical development and practical construction of subway system in soft clay area.

This book can be used as a textbook for graduate students of geological engineering, geotechnical engineering, tunneling engineering, and disaster prevention engineering. Meanwhile, it can be applied as a reference for technical staffs and managers in the practical construction.

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