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 micro-testing 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.

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