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Deformation Characteristics of Surrounding Rock of Marine Soft Soil Tunnel Under Cyclic Loading

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Abstract: Soft marine soil exhibits unique mechanical properties that can lead to significant deformation and instability in the surrounding rock of urban subway tunnels. This presents a critical challenge for tunnel engineering researchers and designers. This thesis investigates the stability characteristics of surrounding rock in marine soft soil tunnels under cyclic loading conditions. Focusing on the shield tunnel segment between Left Fortress Station and Taiziwan Station of Shenzhen Urban Rail Transit Line 12, a discrete–continuous coupled numerical analysis method is employed to examine the deformation characteristics of the surrounding rock. This analysis takes into account the effects of dynamic loads resulting from train operations on the arch bottom's surrounding rock. The findings indicate that damage to the surrounding rock occurs gradually, with the marine soft soil layer, particularly at higher water content, being prone to substantial plastic deformation. Additionally, under the influence of train vibration loads, the degree of vertical fluctuation in the internal marine soft soil diminishes with increasing depth from the bottom of the tunnel arch. This coupled numerical analysis approach offers valuable insights and methodologies for assessing the structural safety of tunnel projects throughout their operational periods.

Keywords: deformation characteristics; discrete–continuous coupled; marine soft soil; numerical analysis; tunnel

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1. Introduction

China's coastline extends approximately 18,000 km, and the coastal economy plays a vital role in the nation's overall economic landscape. Coastal cities have been pivotal in driving rapid economic and social development in recent years. The expansion of underground space and the construction of rail transit systems in these urban areas not only enhance transportation efficiency but also serve as key indicators of a country's technological advancement and overall strength in transportation infrastructure. However, engineers and builders encounter unique challenges when developing underground space and rail transit systems in coastal cities. The prevalence of marine soft soils in these regions poses significant obstacles due to their distinct engineering properties, including low shear strength, high compressibility, and high water sensitivity [1,2]. Subway construction on these soft soil foundations is particularly vulnerable to foundation instability and structural damage, raising serious concerns regarding the safety and reliability of such projects. In response to these challenges, the discrete–continuous coupled numerical analysis method offers innovative approaches to understanding the stability characteristics of marine soft soil tunnels under cyclic loading conditions.

Currently, most numerical computational analysis methods, such as the finite element method (FEM) and finite difference method (FDM), are commonly employed to study the stability of marine soft soil tunnels. However, with advancements in computational technology, the discrete element method (DEM), which effectively simulates the behavior of granular materials and complex physical phenomena, has emerged as a powerful tool for analyzing the dynamics of marine soft soils [3]. A numerical method utilizing an

elasto-plastic constitutive model that characterizes the mechanical properties and structural features of natural clays has been employed to investigate how additional loads impact soil and tunnel displacements in soft ground layers [4]. Furthermore, the risk of insufficient bearing capacity in soft marine soils during tunnel boring machine (TBM) operations has been examined through analytical equations and three-dimensional numerical analyses that simulate dynamic conditions associated with TBM propulsion [5]. In Nansha, Guangzhou, theoretical and numerical analyses, complemented by monitoring data, have been used to investigate the causes of formation collapse during the construction of hydropower tunnels in marine soft ground strata, leading to the proposal of relevant countermeasures [6]. While the aforementioned studies predominantly utilize continuous element numerical methods, discrete element analysis also plays a critical role in various scientific research fields. For instance, Jian et al. [7] established particle flow code (PFC) models for sandy soils and clays, focusing on different particle contact relationships to conduct preliminary studies on soil mechanical properties. These studies demonstrated the effectiveness of PFC in simulating the mechanical behavior of granular materials and provided valuable insights for both theoretical and practical applications in geotechnical engineering. Additionally, a multi-scale coupling analysis scheme that integrates three-dimensional PFC with fast Lagrangian analysis of continua (PFC-FLAC) has been developed to simulate the earth pressure balance (EPB) shield tunneling process, proposing a method for evaluating face stability based on the velocity state of soil particles entering the soil tank [8]. The safety and stability of existing structures during shallow tunnel excavation in urban areas have also been analyzed using the discrete element method to model the motion and interaction of circular particles in soft marine soils [9]. Moreover, numerical methods employing the elasto-plastic constitutive Shanghai model have been utilized to simulate soil responses and assess the effects of repeated surface surcharge loads on soil and tunnel displacements [10]. Despite the significant advantages of particle flow methods and related software in studying geotechnical engineering properties, there remains a notable gap in their application to the stability analysis of marine soft soil tunnels [11].

While extensive research has been conducted both domestically and internationally on the mechanical properties of marine soft soil and the deformation characteristics of tunnel surrounding rock, there is a relative scarcity of studies that examine the deformation and damage mechanisms of surrounding rock in marine soft soil using the discrete element method in detail. To fill this gap, this study draws on a typical subway tunnel project and employs a discrete–continuous coupled numerical analysis method to investigate the deformation behavior of surrounding rock within marine soft soil layers. The findings offer novel research methodologies and insights into the stability of peripheral rock in marine soft soil tunnels, providing a valuable theoretical foundation for the design and construction of subway tunnels in Chinese coastal cities.

2. Numerical Calculation Models and Analysis Methods

2.1. Project Overview

Shenzhen is located in the Pearl River Delta region, an area characterized by extensive marine-phase soft soils, which pose significant challenges to local engineering projects. The construction of rail transit systems in Shenzhen is particularly affected by these soft soils. This paper focuses on the shield tunnel section between Left Fortress Station and Prince Bay Station on Shenzhen Metro Line 12, investigating the deformation mechanism of marine-phase soft soil in this area. The interval between Left Fortress Station and Prince Bay Station passes under the sea, where the presence of silty clay with low shear strength, high compressibility, and high water sensitivity poses serious risks to project safety. Specifically, the section traverses the marine area near Sanwan Wharf, where the excavation process is significantly influenced by the properties of the soft soil. These conditions increase the likelihood of foundation instability and structural damage, presenting a considerable threat to the safety and reliability of the tunnel construction.

Figure 1 presents a schematic diagram illustrating the distribution of geotechnical strata along the tunnel shield interval from Left Fortress Station to Prince Bay Station, passing through the Sanwan Ferry Terminal area. The primary geotechnical strata in this region consist of vegetal fill, silt, marine soft soil, strongly weathered granite, and slightly weathered granite. Additionally, there is hydraulic connectivity between groundwater and seawater in this area. The shield tunnel crosses the Sanwan Ferry Terminal area, predominantly through the marine-phase soft soil stratum.

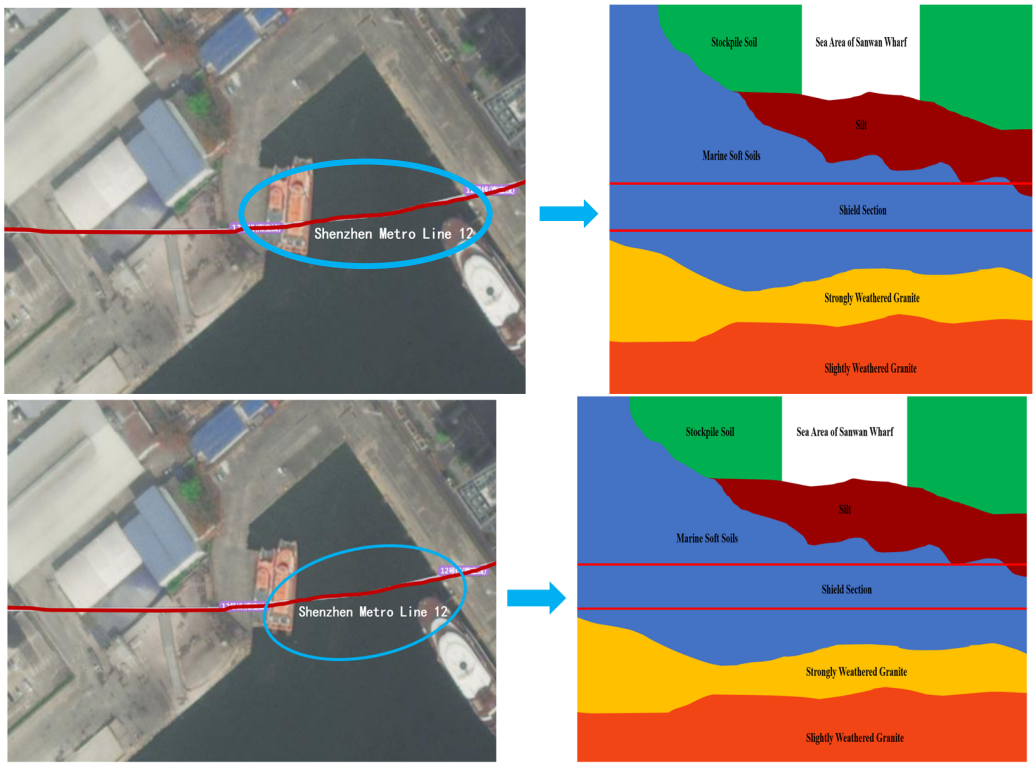


Figure 1. Schematic diagram of the distribution of geotechnical strata.

The left line of the Zuotai interval of Line 12 has a total length of approximately 908.96 m, while the right line measures about 913.18 m. Notably, the left line features approximately 158.56 m of underwater alignment, whereas the right line extends about 185.49 m underwater. The construction of this interval is carried out using the shield method, with two sets of mud–water balanced shield machines tasked with the excavation.

2.2. PFC2D and FLAC2D Coupling Principle

Fast Lagrangian Analysis of Continua (FLAC) is a numerical modeling tool based on the explicit finite difference method, with its primary advantage being the ability to analyze the macroscopic mechanical behavior of continuous media. FLAC is capable of simulating the nonlinear, time-dependent behavior of materials, as well as complex contact and interfacial problems, particularly in soils and rocks. It offers a comprehensive library of material models, supporting a range of behaviors from simple elasticity to complex plasticity and creep. A key feature of FLAC is its high degree of customizability through the FISH programming language, allowing users to develop custom models or analytical functions as needed. In contrast, the Discrete Element Method (DEM) is well suited for solving problems involving discontinuous media. Combining FLAC with DEM leverages the strengths of both methods. For example, in tunnel excavation simulations, the discrete elements can model the soil around the tunnel, while continuous elements represent the intact continuum further from the excavation. This approach allows for

detailed observation of soil collapse and failure, while optimizing computational time and maintaining accuracy [12–14].

2.3. Modeling of Discrete–Continuous Coupling

To accurately simulate the engineering site conditions, a two-dimensional discrete–continuous coupling model with dimensions of 80 m × 80 m was established. The tunnel, modeled as a circular structure with a diameter of 4 m, is positioned at a depth of 15 m. Discrete particles are generated within a 20 m × 20 m area surrounding the tunnel, with the surrounding strata represented by PFC2D particle elements. The remaining strata and tunnel structure are modeled using FLAC solid elements.

The boundary conditions of the model are as follows: horizontal displacement is constrained at the left and right boundaries, while vertical displacement at the bottom is fixed. Figure 2 presents the numerical model. The continuous domain is based on the Mohr–Coulomb constitutive model, with stratigraphic parameters drawn from geological data of similar near-coastal engineering projects [3], as outlined in Table 1. For tunnel support, continuous elements simulate concrete lining segments of varying strengths, with elasticity assumed for the lining materials. The strength and parameter values for the support segments are listed in Table 2.

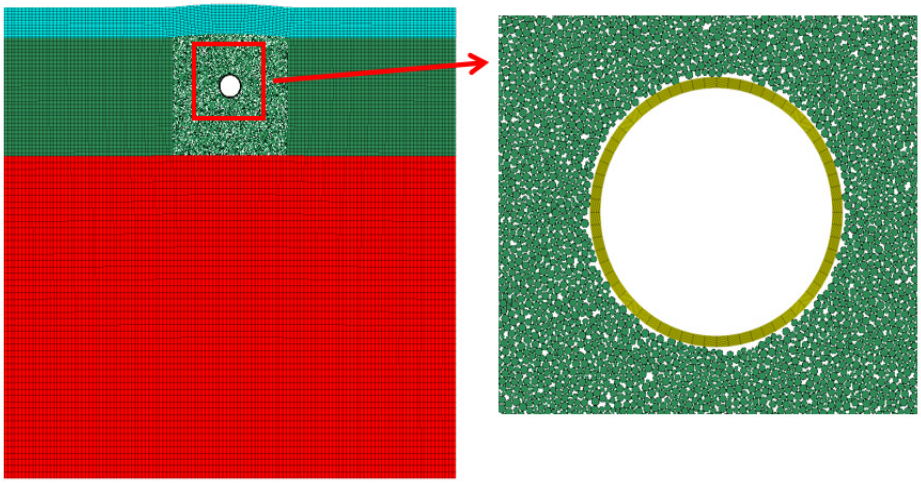


Figure 2. Coupling model.

Table 1. Parameters of each layer.

Stratigraphic Name	Average Thickness (m)	Severe (kN/m^3)	Cohesive Force (kPa)	Internal Friction Angle (°)	Elastic Modulus (MPa)
Stockpile Soil	5	18	10	9	12
Marine soft soils	20	16.5	10	5	6
Strongly weathered rocks	55	19.5	18	15	25

Table 2. Strength and parameter values of concrete support pipe segments.

Concrete Type	Severe (kN/m^3)	Elastic Modulus (GPa)	Poisson's Ratio
C30	25	31.5	0.2
C40	25	33.5	0.2
C50	25	35.5	0.2
C60	25	37.5	0.2

In the PFC particle flow model, specific parameters for the particle units cannot be directly assigned to replicate the macroscopic properties of the soil. Instead, it is

necessary to establish a correlation between the model's fine-scale parameters and the actual physical and mechanical properties of the soil. This requires an iterative process of adjusting the fine-scale parameters until the numerical simulation results accurately reflect the macroscopic physical and mechanical behavior of the soil—this process is known as macro–fine parameter calibration. The key microscopic parameters in the linear contact bond model include the friction coefficient, linear contact effective modulus, the ratio of normal to tangential contact stiffness between particles, normal bond strength, and tangential bond strength. By fine-tuning these microscopic parameters, the numerical results can be brought into closer agreement with the results from laboratory tests. The calibrated fine-scale parameters are listed in Table 3 [3].

Table 3. Calibration results of microscopic parameters.

Sample State	Coefficient of Friction	Linear Contact Effective Modulus (MPa)	Rigidity Ratio	Normal Bond Strength (kPa)	Tangential Bond Strength (kPa)
Water content 40%	0.17	50	2	30	30
Water content 45%	0.15	40	2	25	25
Water content 50%	0.14	20	2	20	20
Water content 55%	0.13	10	2	10	10
Water content 60%	0.11	8	2	1	1

During the research process of this paper, the influence of various parameters in Tables 1–3 on numerical simulation has been discussed in related papers [15]. In this paper, we focus on the deformation characteristics of the surrounding rock of the sea-phase soft soil tunnel under the action of train dynamic load, in which the dynamic load and water content are the two parameters focused on the discussion, and other parameter variability is not considered for the time being.

In this study, a scaled-down model based on the centrifuge principle was used, with a reduction ratio of 1:100. This scaling significantly reduces the number of particles in the model, bringing the total number of particles in the discrete domain down to 42,676, which effectively controls the computational complexity while maintaining a high level of detail. The use of this reduced-scale model not only enhances computational efficiency but also enables accurate simulation of the deformation characteristics of the ground surrounding the tunnel, even with limited computational resources.

To ensure that the mechanical response of the scaled model corresponds to that of the full-scale model, the stress levels within the strata are kept constant. Given the reduced dimensions of the scaled model, the gravitational acceleration is increased by a factor of 100 to match the stress conditions in the actual setting. This approach has been widely used in similar simulations [16]. Although the model is scaled down, the physical and mechanical properties of the materials, such as elastic modulus and Poisson's ratio, remain unchanged. This adjustment ensures that the stress state in the formation is consistent, allowing the scaled model to accurately represent the behavior and response of the soil under real-world stress conditions.

3. Results

3.1. Deformation Characteristics of Particle Flow in Tunnel Surrounding Rock

The failure of the surrounding rock is a gradual process, and the destabilized zones of the surrounding rock at various time steps under unsupported conditions are shown in Figure 3. From the figures, it is evident that the coupled model effectively simulates the tunnel excavation process without support. At the 1000th time step, the destabilized zone is concentrated around the tunnel arch. In the early stages of excavation, the arch particles experience contact failure due to the influence of self-weight. Under unsupported conditions, a temporary pressure arch forms in the surrounding rock, providing brief stability. As time progresses and the stress field evolves, the destabilized zone begins to expand outward. Its shape gradually develops into an ellipsoid with the vertical axis as

the long axis. By the 6000th time step, the destabilized zone has extended to the surface, indicating that the range and severity of destabilization increase with continued excavation.

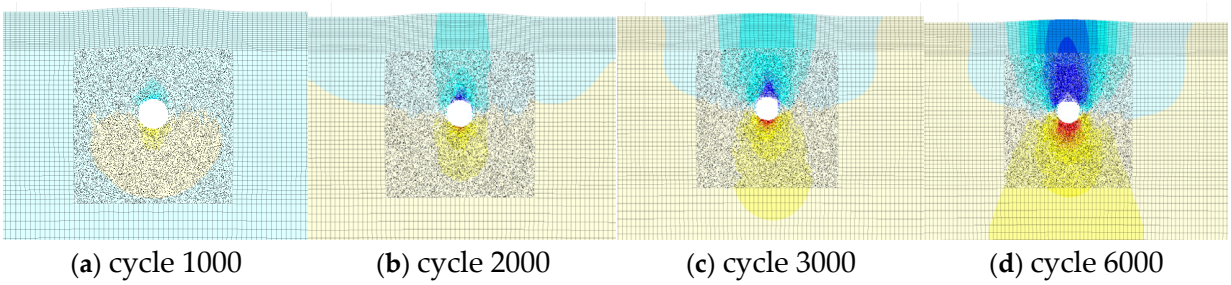


Figure 3. Distribution of surrounding rock instability zone in unsupported state of coupled model.

Liang Xiaodan et al. [17] defined the location where the surrounding rock's shear stress returns to the original rock stress level as the inner boundary of the pressure arch. Under specific conditions, after tunnel excavation, the surrounding rock can achieve a stable equilibrium state through stress redistribution. In the case of unsupported excavation, the variation of shear stress in the surrounding rock is measured through the simulation process, and the resulting shear stress change curves at different distances from the top of the arch are shown in Figure 4. As depicted in the figure, the shear stress in the surrounding rock within 2 m of the arch decreases rapidly over a short period, indicating that this section of rock is bearing significant loads during the initial stages of tunnel excavation. This emphasizes the importance of ensuring that support measures applied during excavation can withstand these initial loads. As the simulation progresses, the shear stress in the surrounding rock at 10 m above the arch and beyond gradually decreases, eventually extending to the surface.

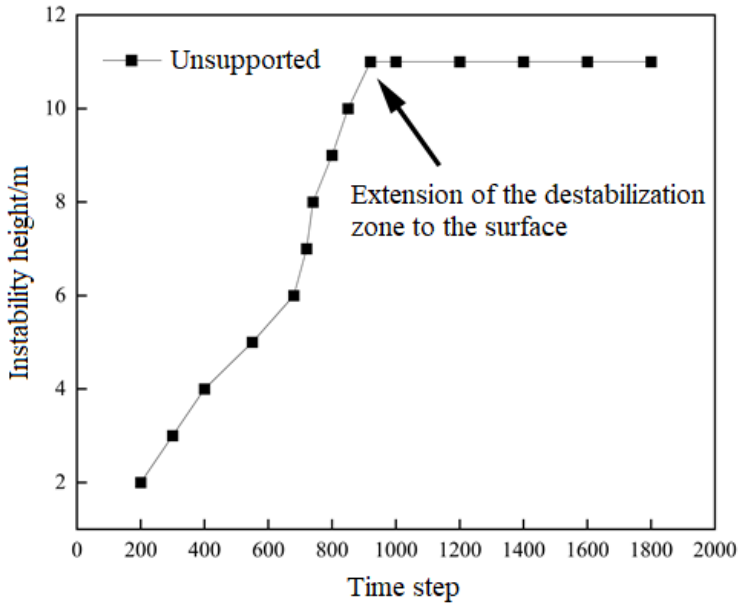


Figure 4. Height change curve of the destabilization zone.

Figure 5 illustrates the force chain diagram of particles after excavation. In the PFC2D-generated force chain diagram, black line segments represent contact forces in compression, with the width of each segment indicating the magnitude of the contact force. As shown in the figure, the force chains in the vault area are relatively sparse, indicating lower contact forces in this region. In contrast, the force chains in the arch waist area are wider and denser, reflecting higher contact forces. Analyzing the force transfer paths reveals that, prior to

excavation, the force was primarily transferred vertically downward. After excavation, the force transfer paths significantly deflected around the excavated zone, suggesting that this deflection is the key factor in the formation of the pressure arch. This change in force transfer indicates that the stress state of the surrounding rock was redistributed during excavation, leading to the formation of a new stabilizing structure—the pressure arch—that effectively supports the weight of the overlying soil and other loads.

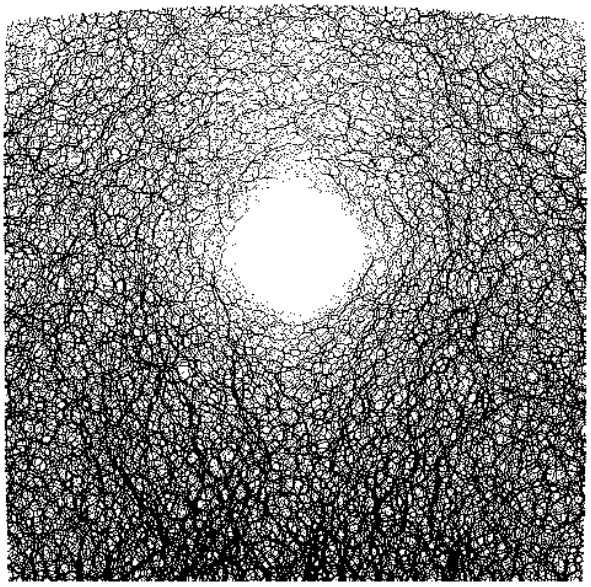
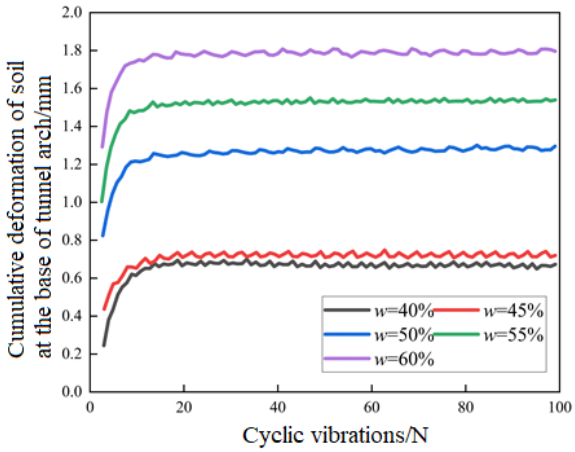


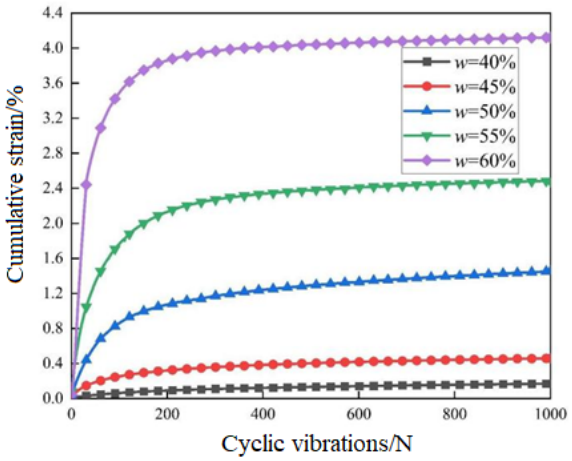
Figure 5. Force chain diagram for discrete particles after tunnel excavation.

3.2. Deformation Characteristics of Tunnel Surrounding Rock Under Different Water Content Conditions

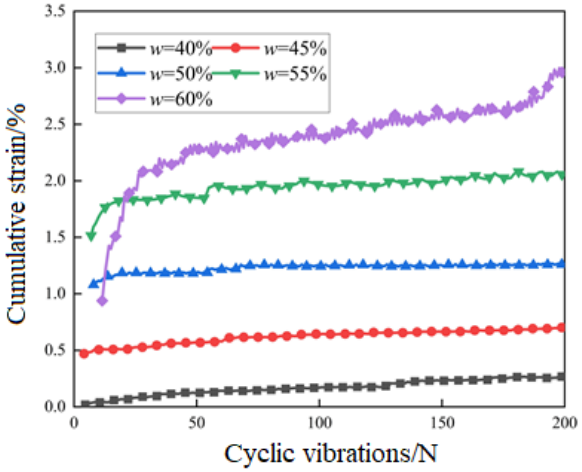
To analyze settlement deformation at a depth of 4 m beneath the tunnel arch in the coupled PFC2D and FLAC2D model, the cumulative deformation of the soil is transformed into positive values and extracted. The cumulative deformation curves under different water content conditions are shown in Figure 6a. These curves are compared with indoor test results under similar water content conditions (Figure 6b) and with discrete element simulation results (Figure 6c). The comparison reveals a clear consistency between the cumulative deformation trends from the coupled model and the results from both the indoor tests and discrete element simulations. This comparison not only confirms the reliability of the coupled model in simulating cumulative deformation at the arch bottom, but also emphasizes the applicability of the results from indoor tests and discrete element simulations within the coupled model. In all approaches—indoor tests, discrete element simulations, and the coupled model—the soil samples exhibited irreversible deformation accumulation under repeated loading conditions. The accumulation of plastic strain was proportional to the water content, with the most significant increases occurring in the early stages of loading. As loading cycles increased, deformation stabilized across all models. These findings suggest that the deformation response at the tunnel arch bottom in the coupled model reflects not only a macroscopic mechanical response, but also the interaction between microstructural changes and the macroscopic mechanical properties of the soil. Indoor tests provide an intuitive understanding of the macroscopic behavior of the soil, while discrete element simulations offer insights into particle-level interactions. The tunnel coupling model integrates these approaches, further validating the deformation characteristics of the soil.



(**a**) Cumulative soil deformation at 4 m at the base of the arch



(**b**) Cumulative strain curve of indoor test



(**c**) Discrete element simulation of cumulative strain curves

Figure 6. Comparison of cumulative deformation of different models.

3.3. Deformation Characteristics of Surrounding Rock at the Bottom of Tunnel Arch Under Cyclic Load

In investigating the stability of marine soft soil tunnels under dynamic train loading, two key factors—water content of the marine soft soil and the distance from the train's point of action to the bottom of the arch—are critical for understanding tunnel stability under such conditions. To explore these factors, relevant measurement points were established within the numerical model, and boundary conditions corresponding to the train load

were applied. This allowed for a detailed numerical simulation of the marine soft soil characteristics. The subway vibration load was simulated by applying a velocity at the bottom of the tunnel, with common displacements observed to range from 1 to 3 mm. For the cyclic loading scenario, the vibration displacement at the bottom of the arch was controlled at 2 mm, with a real-time cycle length of 0.04 s, repeated for a total of 100 cycles [18,19]. Additionally, measuring points were established in the soil at the bottom of the arch to analyze the deformation patterns around the tunnel under varying moisture content conditions. The analysis focused on the deformation behavior of the soil surrounding the tunnel under subway vibration loading, as illustrated in Figure 7.

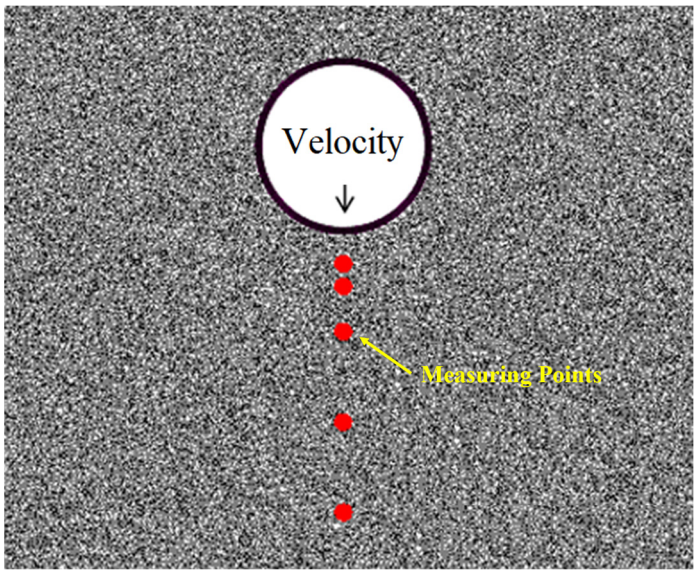
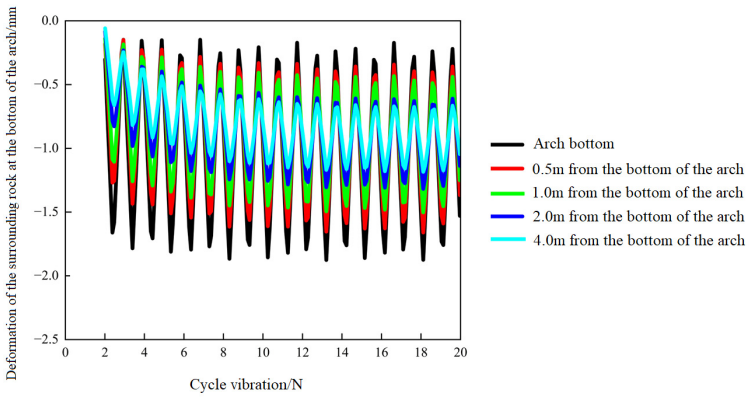


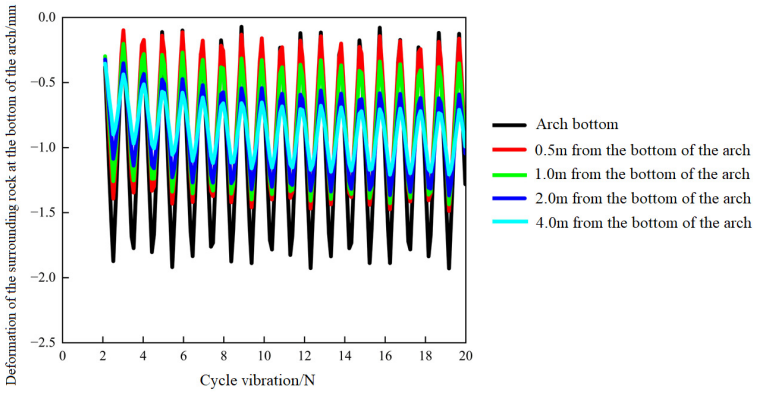
Figure 7. Schematic diagram of measuring point.

Figure 8 shows the displacement curves at different depths of the arch base under 100 cycles of loading conditions. The velocity applied in the simulation is intended to simulate the vibration generated during the operation of the subway, which is able to propagate through the soil body, leading to interactions and displacements between particles. It can be seen that as the number of vibrations increases, the particles within the soil rearranges and produces plastic deformation. The initial vibration may lead to relative displacements between the particles, and as the vibration continues, these displacements accumulate leading to changes in the structure of the soil body and the formation of plastic deformations, and the results obtained are consistent with the results of the triaxial test simulations [3].

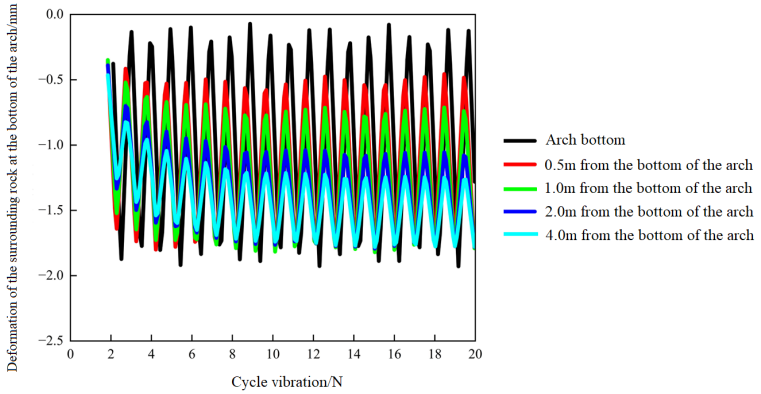


(**a**) Plot of settlement deformation at different depths for w = 40%

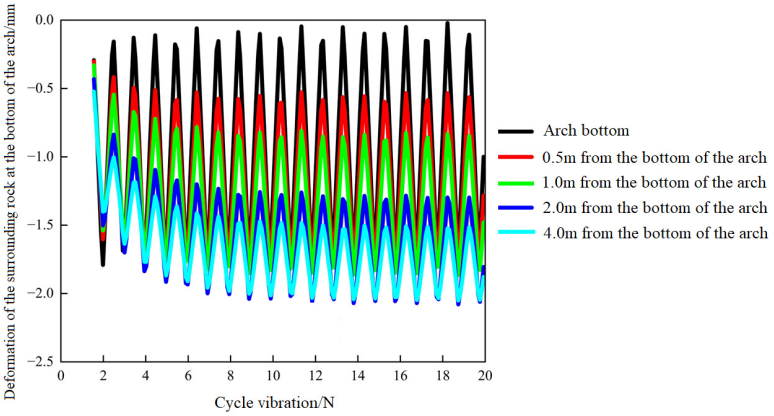
Figure 8. *Cont.*



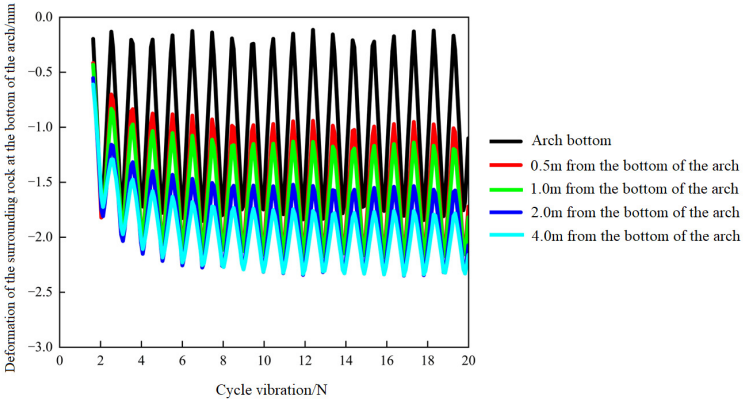
(**b**) Plot of settlement deformation at different depths for w = 45%



(**c**) Plot of settlement deformation at different depths for w = 50%



(**d**) Plot of settlement deformation at different depths for w = 55%



(**e**) Plot of settlement deformation at different depths for w = 60%

Figure 8. Settlement deformation of arch bottom under different moisture content conditions.

The deformation of marine soft soil at the base of the tunnel arch decreases with increasing distance from the arch base, while it increases with higher water content. During cyclic loading, the degree of upward and downward fluctuations in the soft soil diminishes as the depth from the arch base increases. This behavior is attributed to the attenuation of vibration load propagation with depth; particles located deeper within the marine soft soil are less affected by vibrations, resulting in comparatively smaller displacements and deformations. Consequently, the impact of vibration perturbations on the marine soft soil decreases with depth. As the number of vibration cycles increases, the plastic deformation of the soil also rises. This cumulative effect arises because each vibration induces minor displacements in soil particles, which accumulate over multiple cycles, leading to significant plastic deformation. This effect is particularly pronounced under conditions of higher water content, where the reduction in friction between particles further enhances soil susceptibility to deformation under external loads. As water content increases, the shear strength of the soil decreases, making it more prone to larger plastic deformations under the same vibration load.

4. Conclusions

Constructing subway tunnels on marine soft ground frequently poses challenges due to severe foundation deformation. To address this, we developed a discrete–continuous coupled model to investigate tunnel envelope deformation under cyclic train loading, with a particular focus on water content variation. This approach offers an innovative framework for researching and understanding the stability of marine soft soil tunnels. Our findings indicate that the discrete–continuous coupled numerical method is an effective tool for assessing marine soft soil tunnel stability at the microparticle level. This method allows for a more comprehensive and precise understanding of deformation laws in marine soft soil from both macroscopic and microscopic perspectives, providing a valuable theoretical foundation for subway tunnel research and design. Furthermore, our analysis shows that water content and cyclic train loading are critical factors that significantly impact deformation of the tunnel perimeter rock. To mitigate deformation during subway construction, reinforcement measures—such as pre-injection grouting around the tunnel and an overrunning support system within the tunnel—can be implemented to enhance the stability and safety of tunnels under dynamic train loading.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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