A Numerical Investigation of the Deformation Mechanism of a Large Metro Station Foundation Pit under the Influence of Hydromechanical Processes

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1. Introduction

With the acceleration of China’s urbanization, the construction of transportation and other infrastructure is rapidly increasing. At the end of 2020, a total of 45 cities in mainland China had opened 7978.19 km of rail transit lines, including 6302.19 km of subway lines. The strata encountered during the construction of subway tunnels mostly consist of composite strata, such as soil-soil composite strata, rock-rock composite strata, and soil-rock composite strata. It is more difficult to construct subway tunnels and subway stations in soil-rock composite strata than other strata due to the typical characteristics of these strata. Particularly for subway transfer stations with multiple lines, due to the large scale, deep construction depth, and high construction difficulty of these stations, increasing attention has been given to the stability of foundation pit slopes during construction in soil-rock composite strata. Due to the characteristics of the soil-rock composite stratum, which is soft at the top and hard at the bottom, the upper soft stratum tends to soften and collapse when exposed to water, which causes reduced strength and bearing capacity. The lower layer of a
strongly weathered rock mass has high permeability, so landslides and collapse of the foundation pit easily occur in water conditions [1]. In conditions of heavy rainfall, the mechanism of landslide and collapse accidents of deep and large foundation pits in soil-rock composite strata is still ambiguous.

Many scholars have conducted research on the engineering properties of unsaturated soil in rainfall conditions. Based on a numerical study of the coupling of seepage and deformation, Yao et al. [2] discussed the influence of stress-related water retention on the suction distribution and land subsidence during rainfall and evaporation. The numerical results show that, compared with the traditional method without the stress effect, current analyses that consider the influence of stress on the water retention capacity can predict higher foundation undulation and larger foundation settlement. Rahardjo et al. [3] discussed the variability of saturated and unsaturated properties of residual soil with varying depth via laboratory experiments and introduced the variable range and properties of the soil-water characteristic curve (SWCC) of residual soil in Singapore. Based on the Green-Ampt model, Pan et al. [4] comprehensively considered the slope’s initial water content, groundwater level, and unsaturated characteristics and established an infiltration model that is suitable for different rainfall conditions. This model is employed to analyze the granitic residual soil slope for three typical rainfall conditions in southern Jiangxi, China. Zhai et al. [5] quantified the SWCC variability and hydraulic conductivity of residual soils and compared them with the uncertainty of saturated soil properties. This research analyzed the physical and mechanical properties of soil under the influence of rainfall.

Many scholars have also conducted theoretical and experimental studies of slope stability under the influence of rainfall. Based on the improved Green-Ampt (GA) model of rainwater infiltration, Han et al. [6] obtained the analytical expression of the rainwater infiltration volume with varying depth and time in heavy rainfall conditions. The theoretical derivation of rainfall infiltration is verified by numerical simulations and applied to quantitatively analyze the influence of changes in the hydraulic conductivity level on slope stability. He et al. [7] analyzed the characteristics and influencing factors of the saturated zone of soil slopes and analyzed the relationship between the soil permeability coefficient and the rainfall intensity. The results indicate that similar to a slope of 40 degrees, it is easy for the shallow saturated zone to form for a slope of 30 degrees and the previous rainfall after more than 16 days has minimal impact on the critical curve. Karim et al. [8] discussed a simplified numerical method for predicting weather-induced pore water pressure changes in soil slopes. The analysis was then extended to predict the behaviors of soil slopes in two future climate extremes. Based on the principle of saturated infiltration and the Green-Ampt model, Liu et al. [9] established an unsaturated infiltration model of soil slopes, where the water content was constant or changed with depth. By analyzing the change in the initial water content of the slope, the sedimentation time, infiltration depth, and infiltration rate of an unsaturated soil slope after rainfall infiltration can be deduced. Ng et al. [10] proposed a groundwater level assessment system that responds to daily rainfall to predict the slope stability. The system consists of three important components, namely, the conceptual multtank model, unsaturated saturated seepage analysis, and stability analysis. To analyze the impact of extreme rainfall on the recurrence of slope instability, Sengani and Mulenga [11] analyzed historical rainfall data in the study area from 1988 to 2018. In the area from sunny to rainy conditions, the SLIDE simulator was utilized to estimate the slope factor of safety (FoS) of silt clay, clay, and clay loam soils. Cai et al. [12] used an ABAQUS UMAT subroutine for the secondary development of the established coupled hydromechanical constitutive model of unsaturated soil, which considers the effect of the microscopic pore structure. The developed numerical program was employed to simulate the rainfall infiltration process of an actual slope engineering example, and the influence of rainfall intensity and rainfall duration on the pore pressure, velocity, and displacement of unsaturated soil slopes was analyzed. Zhang et al. [13] utilized the PLAXIS finite element software to establish a numerical model and explored the mechanism of rainfall infiltration, which exacerbates the deformation of foundation pits in unsaturated residual soil based on transient seepage analysis. The results show that rainfall infiltration will significantly aggravate the deformation of a foundation pit in unsaturated residual soil and reduce the stability of the foundation pit. Most studies on slope stability under the influence of rainfall focus on soil slopes. There are relatively few studies on soil-rock composite slopes, especially the slopes of foundation pits of deep subway stations.

Some scholars have also conducted related research on subway construction in soil-rock composite strata. Wang et al. [14] proposed a Bayesian network-based method to analyze the factors that affect the surface settlement of shield tunnel construction in the upper-soil and lower-hard strata of soil and rock. Lin [15] investigated the displacement of a retaining structure and the supporting shaft during the excavation process of foundation pits in upper-soil and lower-hard strata by tracking the monitoring data of different measuring points at different stages and analyzing their spatial effects. The research results show that when the shallow soil of the foundation pit is excavated, the impact on the retaining
structure of the foundation pit and the surrounding environment is small, and the retaining structure of the foundation pit will produce a large side shift increment when the silt soft soil layer in the middle of the foundation pit is excavated. To investigate the effect of alternating soft and hard strata on the stability of rock surrounding tunnels, Yang et al. [16] carried out physical experiments and numerical simulations to simulate tunnel excavation in slanted upper-soft and lower-hard strata. Both the physical results and the numerical results revealed that the final failure model shows obvious asymmetrical deformation; the soft rock area experiences block dropping and roof falling, while the hard rock only shows shrinkage deformation. These studies are mostly aimed at the construction of building foundation pits or shield tunnels. Further research on the analysis of the construction mechanics process of deep and large foundation pits in soil-rock composite strata is required.

Methods such as physical model experiments [17–21], seepage experiments [22, 23], numerical simulations [24–28], neural networks [29, 30], and Bayesian networks [31] have all been employed in the study of slopes and foundation pits. However, most previous studies conducted separate tests, simulations, and analyses for a single problem. Research on the slope instability of deep and large subway stations in various conditions is still needed.

The instability mechanism of foundation pit slopes in soil-rock composite strata, especially in heavy rainfall conditions, is still unclear. Due to the difference in the hydraulic conductivity and strength of soil-rock strata, the laws of foundation pit collapse and instability in hydromechanical conditions still require further exploration. In this paper, a numerical simulation study is carried out on the hydraulic coupling and failure mechanism of deep and large foundation pits of subway stations in soil-rock composite strata under heavy rainfall. A finite element numerical model is established based on the engineering example of deep and large foundation pits. The seepage boundary and infiltration value are utilized to realize short-term heavy rainfall. Considering the difference in hydraulic conductivities between different rock and soil layers in the upper-soft and lower-hard strata, the fluid-solid coupling simulation of the deep and large subway foundation pit excavation for the condition of hydromechanical processes is realized. The pore pressure, displacement, and other parameters are compared and analyzed in different conditions based on different excavations depths and rainfall timings, and the law of instability of deep and large subway foundation pits caused by construction after rainfall is studied. The research results can provide a reference for the construction of deep and large foundation pits affected by rainfall in similar soil-rock composite strata.

2. Project Profile

Based on the actual engineering process of the Anshan road station on Qingdao subway line 4, a numerical simulation
study of a large deep foundation pit in soil-rock composite strata under the influence of hydromechanical processes is carried out in this paper. The Anshan road station of Qingdao subway line 4 is a large transfer station of Qingdao subway lines 4 and 8. The east-west and north-south directions of the station intersect in an L shape, as shown in Figure 1. Because the station is a transfer station and the Qingdao subway is generally buried deep, the deepest excavation of the foundation pit is more than 40 m, and the area exceeds 10,000 m². The foundation pit of the Qingdao subway is currently known as the deepest open-cut foundation pit in the soil-rock composite strata in Shandong Province, China [32].

Qingdao City, Shandong Province, China, where the station foundation pit is located, has a typical temperate maritime climate that is characterized by a humid climate and heavy rainfall during the rainy season. The flood season is concentrated from July to September, and the rainfall in the flood season accounts for more than 70% of the annual rainfall. According to the annual hydrological report issued by the Qingdao Hydrological Bureau, the average rainfall in 2020 exceeded 970 mm. The groundwater at the site mainly consisted of pore water and bedrock fissure water, and the groundwater level was approximately 15 m.

According to the geological survey report, the strata at the site mainly consist of plain fill, silty clay, strongly weathered granite, moderately weathered granite, and lightly weathered granite, and joints and cracks are not developed. The plain fill, silty clay, and strongly weathered granite form the "upper soft" part of the soil-rock composite stratum, while moderately weathered and slightly weathered granite form the "lower hard" part; the two parts constitute a typical upper-soft stratum and lower-hard stratum. Due to the large excavation depth and span, the excavation of deep and large foundation pits in this condition is prone to excessive local displacement, which may lead to slope instability and collapse. Coupled with the effect of short-term heavy rainfall, the slope stability is further reduced under the effect of hydraulic coupling.

3. Numerical Simulation

In this paper, the deep and large foundation pit of the Anshan road station of Qingdao subway line 4 is selected as the subject of the numerical simulation of hydraulic coupling of a deep and large foundation pit in soil-rock composite strata for the condition of heavy rainfall. To study the
influence of rainfall on the instability of station foundation pit excavation, the finite element numerical simulation method was employed to establish two sets of comparative numerical models in different conditions, i.e., with rainfall and without rainfall. The pore pressure, displacements, and other parameters were compared and analyzed, and the effect of the specific degree of rainfall on the various parameters was investigated. The steps of the numerical simulation process are shown in Figure 2.

3.1. Numerical Model Construction. Since the deep and large foundation pit of the station is L-shaped in the east-west and north-south directions, for convenience, the two-dimensional numerical calculation of the north-south
Figure 7: Vertical displacement curves with an excavation of 10 m.

Figure 8: Pore pressure with an excavation of 10 m.
foundation pit is simplified such that the model considers only the east-west direction. According to the actual project, the excavation depth $H$ of the foundation pit is 40 m, and the span $D$ of the foundation pit is 36 m. To eliminate the boundary effect, the left and right boundaries of the foundation pit are set to a length of approximately $3D$ and the model height is $2.5H$. The origin of the coordinates is at the center of the foundation pit. The $x$ direction is the horizontal direction, and the $y$ direction is the vertical direction. The ground elevation of the model is 20 m. To simplify the calculation and highlight the impact of rainfall on the instability of the foundation pit excavation, the supporting structure is not considered in the excavation. The final size of the model is $x \times y$, which is equal to $240 \text{ m} \times 100 \text{ m}$, as shown in Figure 3.

According to the project overview, within the scope of the model, there are 5 strata from top to bottom, namely, plain fill, silty clay, strongly weathered granite, moderately weathered granite, and slightly weathered granite. According to the geological survey report, the thickness and physical and mechanical parameters of each stratum are shown in Table 1. The height of the groundwater head is 15 m. According to the numerical simulation road map, it is necessary to establish numerical models for two working conditions with and without rainfall to compare the variation law of various characteristic parameters that are related to foundation pit excavation instability. Displacement constraints are adopted in the model boundaries, in which the bottom boundary is fixed via vertical displacement, the horizontal boundary is fixed via horizontal displacement, and the top boundary is set free. Triangular elements are utilized in the model. There are 1769 nodes and 3405 elements. The numerical model is shown in Figure 4.

3.2. Numerical Simulation of Rainfall. To realize the numerical simulation of rainfall conditions, the seepage boundary and infiltration value are applied to the numerical model. The finite element software RS2 can set the seepage boundary conditions to simulate water seepage. The saturation of different surrounding rock materials is realized by setting different hydraulic conductivities via the software. When the hydraulic conductivities of the surrounding rock materials are fixed, the numerical simulation of rainfall seepage can be realized under the combined action of different infiltration values and changes in pore water pressure caused by excavation. According to the actual rainfall, the maximum rainfall is $200 \text{ mm/d}$, so the infiltration value is $2.3e^{-6} \text{ m/s}$. When rainfall is considered, the seepage boundary and infiltration value are set to excavation depths of 10 m, 20 m, 30 m, and 40 m. The rainfall conditions of the numerical model can be realized using this method.

3.3. Numerical Simulation Method of Hydromechanical Processes. The simulation of hydromechanical processes has always been a difficult problem in numerical simulation. Currently, this simulation is replaced by methods such as setting the groundwater head, seepage boundary, and element fluid flow, and rainfall is often equivalent to these methods via
Figure 11: Vertical displacement curves with an excavation depth of 20 m.

Figure 12: Pore pressure with an excavation depth of 20 m.
flow conversion. These methods have certain errors in the hydraulic coupling calculations; the results provide more reference value than the actual guidance. In this paper, by activating the built-in software’s stress and groundwater coupling calculation options and supplementing the seepage boundary and rainfall flow, the rainfall factor is included while considering groundwater, as shown in Figure 5.

In addition, under the influence of short-term heavy rainfall, due to the different permeabilities of the surrounding rock of the foundation pit, water accumulation is likely to occur at the bottom of the foundation pit. In many studies, the gravity change caused by ponded water is not included in the numerical calculation, and the calculation results often include errors. In this paper, while considering the rainfall flow, the gravity caused by ponded water is also considered. According to site construction experience, the accumulated water at the bottom of the pit under the influence of heavy rainfall is assumed to be 0.5 m. According to the depth of the ponded water at the bottom of the foundation pit, accumulation is applied to the hydraulic coupling calculation, as shown in Figure 6.

4. Analysis of the Numerical Simulation Results

In this paper, a hydraulically coupled finite element numerical simulation for the excavation of deep and large subway station foundation pits in soil-rock composite strata in rainfall conditions is carried out. A comparative analysis of the excavation conditions for different foundation pit depths with and without rainfall is also performed. The supporting structure is not considered during excavation in this simulation, and the default excavation is performed 10 m at a time.

4.1. Analysis of Rainfall Impact with an Excavation Depth of 10 m.

When the excavation depth of the foundation pit is 10 m, the contour map of the vertical displacement of the model with and without rainfall is shown in Figure 7 (to highlight the excavation location, a range of 60 m is applied in the x direction). The pore pressure is shown in Figure 8, and the deformed mesh is shown in Figure 9.

According to the numerical calculation results, when the excavation of the foundation pit is 10 m, the maximum uplift value of the bottom of the pit is 20.5 mm without rainfall and the maximum uplift value of the bottom of the pit is 16.7 mm with rainfall. Rainfall causes the value of the uplift of the pit bottom to decrease. The analysis of the pore pressure shows that when there is no rainfall, the excavation of the foundation pit causes the pore water pressure to decrease; when there is rainfall, the pore pressure of the soil near the ground increases due to the infiltration of rainwater. As the horizontal distance from the foundation pit increases, the pore water pressure at the same depth also increases. From the mesh deformation caused by the excavation of the foundation pit, it is evident that the overall deformation of the foundation pit excavation with rainfall is greater than that without rainfall, but the difference in deformation is not significant. When the horizontal displacements of the pit walls on both sides of the foundation pit are further analyzed, the results
Figure 15: Vertical displacement curves with an excavation depth of 30 m.

Figure 16: Pore pressure with an excavation depth of 30 m.
indicate that the horizontal displacements of the pit walls on both sides are not much different with or without rainfall. After rainfall, the horizontal displacements on both sides increase, as shown in Figure 10. The y-axis is the depth of excavation, which is divided equally by 5 values.

4.2. Analysis of Rainfall Impact with an Excavation Depth of 20 m. When the excavation depth of the foundation pit is 20 m, the contour map of the vertical displacement of the model with and without rainfall is shown in Figure 11 (to highlight the excavation location, a range of 60 m is applied in the x direction). The pore pressure is shown in Figure 12, and the deformed mesh is shown in Figure 13.

According to the numerical calculation results, when the excavation of the foundation pit is 20 m, the maximum uplift value of the bottom of the pit is 10.7 mm without rainfall and the maximum uplift value of the bottom of the pit is 7.6 mm with rainfall. Rainfall also causes the pit bottom uplift value to decrease. The pore pressure analysis shows that when there is no rainfall, the excavation of the foundation pit causes the pore water pressure to decrease; when there is rainfall, the pore pressure of the soil near the ground increases due to the infiltration of rainwater. The overall pore pressure is less than that at an excavation depth of 10 m. From the mesh deformation caused by the excavation of the foundation pit, it is evident that the overall deformation of the foundation pit excavation with rainfall is greater than that without rainfall, and the change in the uplift value of the pit is less than that at an excavation depth of 10 m. When the horizontal displacements of the pit walls on both sides of the foundation pit are further analyzed, the horizontal displacements of the pit walls on both sides are not much different with and without rainfall. After rainfall, the horizontal displacements on both sides increase compared with those before rainfall, and the displacement is concentrated mainly in the first 10 m, which indicates that the sidewall of the foundation pit is unstable at a distance of 10 m from the ground, as shown in Figure 14. The y-axis is the depth of excavation, which is divided equally by 5 values.

4.3. Analysis of Rainfall Impact with an Excavation Depth of 30 m. When the excavation depth of the foundation pit is 30 m, the contour map of the vertical displacement of the model with and without rainfall is shown in Figure 15 (to highlight the excavation location, a range of 60 m is applied in the x direction). The pore pressure is shown in Figure 16, and the deformed mesh is shown in Figure 17.

According to the numerical calculation results, when the excavation of the foundation pit is 30 m, the maximum uplift value of the bottom of the pit is 12.6 mm without rainfall and the maximum uplift value of the bottom of the pit is 8.3 mm with rainfall. Rainfall also causes the pit bottom uplift value to decrease. The pore pressure analysis shows that when there is no rainfall, the excavation of the foundation pit causes the pore water pressure to decrease; when there is rainfall, the pore pressure of the soil near the ground increases due to the infiltration of rainwater. The overall pore pressure is less than that at an excavation depth of 20 m.
Figure 19: Vertical displacement curves with an excavation depth of 40 m.

Figure 20: Pore pressure with an excavation depth of 30 m.
From the mesh deformation caused by the excavation of the foundation pit, it can be seen that the overall deformation of the foundation pit excavation with rainfall is greater than that without rainfall, and the change in the uplift value of the pit is greater than that at excavation depths of 10 m and 20 m. When the horizontal displacements of the pit walls on both sides of the foundation pit are further analyzed, the horizontal displacements of the pit walls on both sides are not much different with and without rainfall. After rainfall, the horizontal displacements on both sides increased compared with those before rainfall, and the displacement was concentrated in the first 13 m. When the excavation depth exceeds 13 m, the horizontal displacement decreases rapidly, which indicates that the sidewall of the foundation pit is unstable at a distance of 13 m from the ground, as shown in Figure 18. The y-axis is the depth of excavation, which is divided equally by 5 values.

4.4. Analysis of Rainfall Impact with an Excavation Depth of 40 m. When the excavation depth of the foundation pit is 40 m, the contour map of the vertical displacement of the model with and without rainfall is shown in Figure 19 (to highlight the excavation location, a range of 60 m is assumed in the x direction.). The pore pressure is shown in Figure 20, and the deformed mesh is shown in Figure 21.

According to the numerical calculation results, when the excavation of the foundation pit is 40 m, the maximum uplift value of the bottom of the pit is 15.1 mm without rainfall and the maximum uplift value of the bottom of the pit is 9.7 mm with rainfall. Rainfall also causes the uplift value of the pit bottom to decrease. The pore pressure analysis shows that when there is no rainfall, the excavation of the foundation pit causes the pore water pressure to decrease; when there is rainfall, the pore pressure of the soil near the ground increases due to the infiltration of rainwater. The overall pore pressure is less than that at an excavation depth of 30 m. From the mesh deformation caused by the excavation of the foundation pit, it is evident that the overall deformation of the foundation pit excavation with rainfall is greater than that without rainfall, and the change in the uplift value of the pit exceeds that of the excavation depths of 10 m, 20 m, and 30 m. When the horizontal displacements of the pit walls on both sides of the foundation pit are further analyzed, the horizontal displacements of the pit walls on both sides are not much different than those with and without rainfall. After rainfall, the horizontal displacements on both sides increase compared with those before rainfall, and the displacement is also concentrated mainly in the first 13 m, which indicates that the sidewall of the foundation pit is unstable at a distance of 13 m from the ground, and the depth is closer to the bottom of the pit. The horizontal displacements of the two sidewalls of the foundation pit are similar before and after rainfall, as shown in Figure 22. The y-axis is the depth of excavation, which is divided equally by 5 values.

4.5. Vertical Displacements of the Pit Bottom. To study the changing law of the vertical displacement at different
positions of the pit bottom with different excavation depths, the vertical displacements of the pit bottom for the conditions of rainfall and no rainfall are selected. The vertical displacement of different positions at the bottom of the pit for different excavation depths with or without rainfall is shown in Figure 23.

As the excavation depth increases, the vertical displacement of the pit bottom decreases. At the same excavation depth, the vertical displacements of different horizontal positions are distributed symmetrically. The vertical displacement of the pit bottom in rainfall conditions is smaller than that in no-rainfall conditions. Except when the excavation depth is 10 m and when the excavation depth is 20 m, 30 m, and 40 m, the vertical displacement of the pit bottom gradually decreases from the center to the two sides.

5. Conclusions

In this paper, a hydraulic coupling numerical simulation study is carried out to investigate the cause of the instability of foundation pit construction for a deep subway station affected by heavy rainfall in a soil-rock composite stratum. Based on the engineering background of the Anshan road subway station on Qingdao subway line 4, a numerical simulation model is established by the finite element fluid-solid coupling method. Typical parameters were analyzed when the soil-rock composite foundation pits were excavated at depths of 10 m, 20 m, 30 m, and 40 m for the condition of heavy rainfall. Via comparative analyses of the vertical displacement, horizontal displacement, pore water pressure, and other parameters, the deformation and laws of instability of deep and large foundation pits in soil-rock composite formations affected by heavy rainfall are analyzed. The main conclusions are presented as follows:

(1) A finite element numerical simulation is used to simulate the excavation of deep and large subway station foundation pits in soil-rock composite strata. When the excavation depths are 10 m, 20 m, 30 m, and 40 m, the uplift values of the foundation pit bottom without rainfall are 20.5 mm, 10.7 mm, 12.6 mm, and 15.1 mm, respectively; the uplift values of the foundation pit bottom with heavy rainfall are 16.7 mm, 7.61 mm, 8.3 mm, 9.7 mm, respectively. The soil-rock composite stratum softens and disintegrates after encountering water, which causes a decrease in shear strength and bearing capacity.

(2) When there is no rainfall, the excavation of the foundation pit will cause the surrounding pore water pressure to decrease, and the groundwater will flow in the foundation pit. During heavy rainfall, the pore water pressure at the surface rises rapidly due to surface seepage, and the pore water pressure decreases as it nears the foundation pit. As the excavation depth increases, the pore water pressure shows a decreasing trend.

(3) The horizontal displacement of the sidewall of the foundation pit increases with an increase in excavation depth. The horizontal displacement occurs mainly in the first 13 m of excavation, and the horizontal displacement decreases rapidly after the excavation exceeds 13 m, which indicates that the sidewall of the foundation pit collapses 13 m from the surface. The depth of instability after rainfall is closer to the bottom of the pit than that before rainfall.
Data Availability

All data supporting this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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