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Review Article

Soil Creep Effect on Time-Dependent Deformation of Deep Braced Excavation

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This paper describes recent advances in the effect of soil creep on the time-dependent deformation of deep braced excavation. The effect of soil creep is generally investigated using the observational method and the plain-strain numerical simulation method. The observational method is more applicable for deep braced excavations in soft clays constructed using the top-down method. The plain-strain numerical simulation method can be conveniently used for parametric analysis, but it is unable to capture the spatial characteristics of soil creep effect on lateral wall deflections and ground movements. The additional lateral wall deflections and ground movements that are generated due to the soil creep effect can account for as large as 30% of the total displacements, which highlights the importance of considering the effect of soil creep in deep braced excavations through soft clays. The magnitude of the displacements due to soil creep depends on various factors, such as excavation depth, elapsed period, unsupported length, and strut stiffness. Parametric analyses have indicated several effective measures that can be taken in practice to mitigate the detrimental effect of soil creep on the deformation of deep braced excavation. Based on the literature review, potential directions of the related future research work are discussed. This paper should be beneficial for both researchers and engineers focusing on mitigating the adverse effect of soil creep on the stability of deep braced excavations.

1. Introduction

Deep braced excavations are ubiquitous in construction engineering such as subway stations [1–3], building basements [4–6], and launch shafts for shield tunneling machines [7, 8]. To facilitate the optimizing of the excavation support system and reduce the potential adverse impact on affected infrastructures, the performance of deep braced excavations has been extensively investigated in the past several decades, on the basis of case studies [9, 10], numerical simulations [11, 12], centrifuge model tests [13, 14], empirical or semi-empirical methods [15, 16], and machine learning predictions [17, 18].

The performance of deep braced excavation was observed to be time-dependent in several practical projects, whereas this time-dependent performance has not been well understood due to the complexity of this problem [19, 20]. The complexity of this problem is primarily attributed to the coupling of the various factors affecting the time-dependent performance of deep braced excavation. Roscoe and Twine [21] found that the movements of the embedded retaining walls for 1.8 km long cut-and-cover tunnels were time-dependent, with a maximum rate of 0.2 mm/day. They stated that this behavior could not be caused by the soil consolidation effect. The results of finite element analysis by Ou and Lai [22] indicate that the maximum wall deflection and ground surface settlement decrease slightly with elapsed time from completing the excavation. This trend was simply attributed to the dissipation of negative excess pore-water pressure on the passive side of the retaining wall as the soil creep effect was not considered in the analysis. Based on limited case histories, Fuentes et al. [23] concluded that the dominant cause for time-dependent wall movements was soil consolidation rather than soil creep.

For a long and deep excavation with four sections in Shanghai soft clay [24], the larger magnitude of wall deflections at a section than other sections were attributed to the relatively longer construction time and apparent creep behavior of Shanghai clay. Based on the results of field observations in Shanghai soft clays, Liu et al. [25] found that the time-dependent ground surface settlements occurring during a 60 days concrete curing period were attributed to the primary consolidation rather than creep effects. For a 13-m-deep excavation in Chicago soft clay reported by Finno et al. [26], 13 mm of the 38 mm of maximum lateral soil movement and 12 mm of the 40 mm of maximum ground surface settlement occurred as a result of soil creep and reduction of wall stiffness. From the studies mentioned above, it can be indicated that the opinions about the effect of soil creep on the time-dependent performance of deep braced excavation are divided. In this case, a review of this topic is necessary for deepening our understanding of the soil creep effect.

In this paper, recent advances in the soil creep effect on the time-dependent performance of deep braced excavation are reviewed. The methods for investigating the effect of soil creep are first described, followed by a discussion of the soil creep effect on retaining wall deflections, ground surface settlements, and basal heaves. Thereafter, a discussion of the countermeasures and recommendations for the potential directions of future research work in this topic are provided.

2. Methods

As the soil creep effect tends to be coupled with consolidation and/or relaxation, the existing analytical solutions for excavation-induced ground and wall responses have hardly taken account of the soil creep effect. Therefore, the methods used for investigating the effects of soil creep on the time-dependent performance of deep braced excavation mainly include the observational method and numerical simulation method. The numerical simulation method can be classified into finite element analysis and finite difference analysis, according to the numerical analysis software adopted such as PLAXIS, ABAQUS, and FLAC. Among them, FLAC is a finite difference analysis software.

2.1. Observational Method. The observational method can provide the real response of ground and excavation support system due to the excavation-induced stress relief, but the observed results of time-dependent performance may be attributed to a combination of various factors when the excavation investigated is not suitable for this method. The observational method is better applicable in a deep excavation constructed using the top-down method in a soft clay stratum with low permeability, where the pronounced time-dependent wall deflections and ground surface settlements are only a result of the soil creep effect.

For a deep braced excavation with the top-down construction method, an elapsed period of more than one month between two successive excavation stages is generally needed for installing struts and pouring concrete floor slab. The elapsed periods without excavating work provide a great opportunity to survey the time-dependent performance. In a soft clay stratum with low permeability, the dissipation of negative excessive pore-water pressure, which occurred during these elapsed periods of no excavating work, is trivial and thus has little effect on the observed time-dependent performance. Moreover, it has been widely acknowledged that the creep effect of soft clay is more obvious than hard soil such as sand and stiff clay [27–29]. As a result, the observational method is more applicable for top-down excavation through soft clay of low permeability. When adopting this method, an accurate measurement of pore-water pressure is indispensable for separating creep from negative excessive pore-water pressure dissipation. The pore-water pressure can be measured by using vibrating wire piezometers [7, 25] or pneumatic piezometers [26, 30]. In addition, inclinometers, vibrating wire strain gauges, and settlement markers can be also installed to measure the variations of lateral movements of wall and ground, forces in selected support members, and ground surface settlements during the elapsed time.

2.2. Numerical Simulation Method. The numerical simulation method has been widely used to investigate the effect of soil creep on the time-dependent performance of deep braced excavation, because of its exclusive capability in parametric analysis. In this method, the critical aspects include the selection of numerical analysis software, the determination of the constitutive models for the ground stratum, and the calibration of the constitutive model parameters.

A summary of the commonly adopted numerical analysis software, soil creep models, and parameter calibration methods are presented in Table 1 for several typical studies in the literature. The FLAC and FLAC 3D are finite-difference method-based numerical analysis software, while the PLAXIS 2D/3D, ANSYS, and ABAQUS are based on the finite element method. These programs are powerful in studying the soil creep effect because of the incorporation of diverse soil creep models. The classical visco-elastic model is the simplest creep model, which includes the parameters of mass density, dynamic viscosity, elastic shear modulus, and elastic bulk modulus. The rate-dependent soil creep model, established based on the constant-stress undrained creep tests [41], consists of an equivalent stress-strain curve and a stress-strain-time function. The soft soil creep model, as an extension of the modified cam-clay model, can account for the creep behavior of nearly-consolidated soil but takes no account of the small-strain stiffness. The Kelvin-Mohr-Coulomb model is a modified version of the CVISC model, which can generate satisfactory results. In addition, the inverse analysis of the observed wall deflections or ground surface settlements is an effective means of calibrating the parameters of the adopted soil creep model.

Table 1: Summary of typical studies using numerical simulation method.

Software	Soil creep model	Parameter calibration method	Reference
FLAC	Classical visco-elastic model	Inverse analysis	[31]
FLAC	Rate-dependent soil creep model	Inverse analysis	[32, 33]
PLAXIS 2D	Soft soil creep model	Based on existing equations	[34]
PLAXIS 2D	Soft soil creep model	Inverse analysis	[35]
PLAXIS 3D	Soft soil creep model	Inverse analysis	[36]
FLAC 3D	Kelvin-Mohr-Coulomb model	Based on experience	[37]
ANSYS	Time-hardening model	Based on triaxial creep testing	[38]
FLAC 3D	Viscoelastic model with five elements	Based on triaxial creep testing	[39]
ABAQUS	Extended Drucker-Prager model	Based on existing equations	[40]

3. Results

Based on the observational method and/or numerical simulation method described above, significant advances have been made in understanding the effects of soil creep on the time-dependent performance of deep braced excavation. This section reviews the achievements that have been made by other researchers and discusses briefly the soil creep effects on wall defections and ground movements.

3.1. Soil Creep Effect on Wall Deflections. The time-dependent lateral wall deflections of the TNEC excavation project were investigated by Lin and Ou [33] adopting the observational method and plain-strain finite difference analysis. The finite-difference analysis with FLAC was made for the main section of observation as depicted in Figure 1(a). Figure 1(b) shows a comparison of the observed lateral wall deflections at I-1 and the calculated results for several typical excavation depths. The results indicate that the lateral wall deflections increased with the elapsed time while the excavation depth kept unchanged. This increase in lateral wall deflection is believed to be caused by the creep of normally consolidated Taipei silty clay considering the fact that the in situ pore-water pressure was observed to be nearly constant during these no-excavation periods. Moreover, the lateral wall displacement induced by the soil creep may account for a large portion of approximately 30% of the total lateral wall deflection.

The soil creep effect on wall deflection varies depending on many factors such as ground conditions, construction methods, strut or slab stiffness, and workmanship. By using FLAC with the build-in rate-dependent soil creep model, a parametric analysis was performed by Kung [32] to investigate the difference of the soil creep effect on the wall deflection between the top-down and bottom-up construction methods through four hypothetical deep excavation cases as illustrated in Figure 2. The four cases include one deep braced excavation constructed using the top-down method (TDM) and three deep braced excavations constructed using the bottom-up method (BUM). The final excavation depths for the four cases are identical with a magnitude of 19 m. The BUM cases consist of three types which are different in the cover depths of steel struts and excavated surfaces. In addition, in the parametric analysis, the influence of floor slab stiffness in the TDM case, as well as, strut prestress, and strut stiffness in the BUM cases is also considered.

Figure 3 shows the influence of the stiffness of floor slab and strut as well as strut prestress on the soil creep effect for the four hypothetical deep excavation cases. For the TDM case, as depicted in Figure 3(a), an increase in the stiffness of the floor slab leads to a slight decrease in the maximum wall deflection, irrespective of whether the creep effect of soil is considered in the numerical analysis. At all the investigated stiffnesses of the floor slab, the maximum wall deflections considering the creep effect are greater than those without the creep effect. In other words, the creep effect of soil results in an additional maximum wall deflection of approximately 35 mm, which is not affected significantly by the stiffness of the floor slab. However, for the BUM cases as shown in Figure 3(b), the additional wall deflection induced by the soil creep decreases observably with increasing the stiffness of the strut. The application of the strut prestress contributes to the restraining of the time-dependent wall deflection induced by the soil creep. Additionally, it seems that the influence of the cover depths of excavated surfaces and steel struts on the incremental wall deflection due to soil creep is more intense at a moderate magnitude of stiffness of strut (e.g., 30 MN/m/m).

To evaluate the effect of soil creep on the wall deflections in a quantitative manner, three parameters, which are creep rate, creep ratio, and total creep ratio, have been defined [34]. The creep rate is defined as the maximum wall deflection caused by the soil creep divided by the elapsed period when the maximum wall deflection occurs, which can be expressed as

$$R_c = \frac{\Delta\delta_{hm}^{cr}}{\Delta t}, \tag{1}$$

where R_c = creep rate; $\Delta\delta_{hm}^{cr}$ = maximum wall deflection caused by soil creep; and Δt = elapsed period during which the maximum wall deflection occurs.

Note that the elapsed period in the definition of the creep rate can be one of the following three cases: (1) the elapsed period between the beginning of excavating and the beginning of installing struts for a construction stage; (2) the elapsed period between the completion of installing struts for the present construction stage and the beginning of excavating for the next construction stage; and (3) the elapsed period between the beginning of excavating for the present construction stage and the beginning of excavating for the next construction stage.

The creep ratio, R_t, is defined as

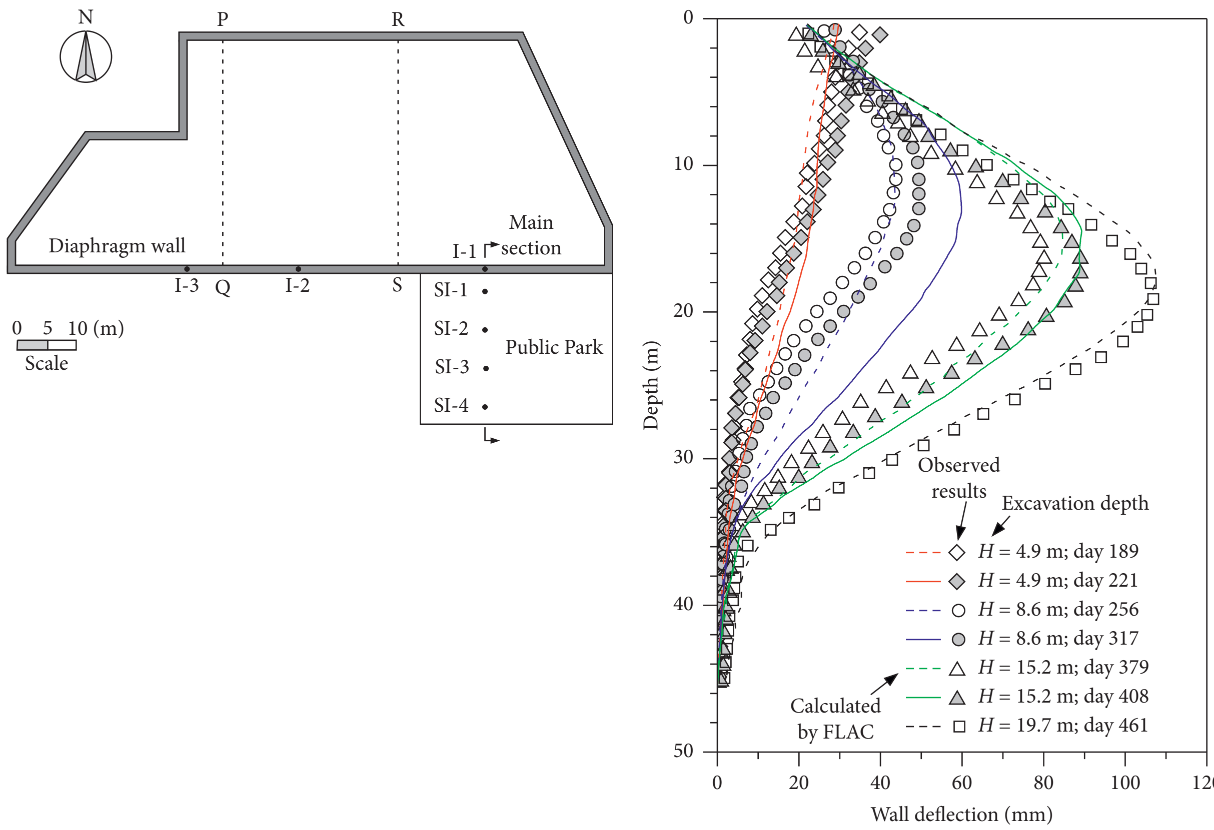

Figure 1: The TNEC excavation project: (a) instrumentation layout; (b) comparison of observed and calculated lateral wall deflections at typical excavation depths, modified from [31].

$$R_t = \frac{\delta_{Ch\max}}{\delta_{h\max}}, \tag{2}$$

where $\delta_{Ch\max}$ = maximum wall deflection caused purely by soil creep at a construction stage and $\delta_{h\max}$ = maximum wall deflection caused purely by excavation at a construction stage.

The total creep ratio is obtained by adding the creep ratios for all the construction stages through

$$R_t^T = \sum_{k=1}^{n} R_t^k, \tag{3}$$

where R_t^T = total creep ratio; n = total amount of construction stages; $k = a$ number ranging between 0 and n; and R_t^k = creep ratio for the k^{th} construction stage.

The creep rate depends on the excavation depth and support stiffness. In general, the creep rate increases as proceeding the excavation depth, and peaks at the final excavation depth. Figure 4 shows a comparison of the creep rates at excavation depths of 6.8, 10, 13.5, 17, and 19.6 m observed in the O6 station excavation project [31]. The creep rate ranges between 0.14 and 0.38 mm/day depending on the magnitude of excavation depth. The magnitudes of the creep rates at the last two excavation depths are found to be lower than that at the excavation depth of 13.5 m, which is inconsistent with the general trend that the creep rate increases as increasing the excavation depth. This inconsistency may be attributed to the movement of the inclinometer toe at deeper excavation depths.

The dimensionless support stiffness, S, defined by Clough and O'Rourke [42] as equation (4) has been used for the description of the relationship between the creep rate and the support stiffness(Chen et al. [34]).

$$S = \frac{EI}{\gamma_w h_{\text{avg}}^4}, \tag{4}$$

where E = elastic modulus of the wall; I = moment of inertia of the wall; γ_w = unit weight of water; and h_{avg} = average of vertical intervals between struts.

Figure 5 shows the effects of the dimensionless support stiffness, S, on the creep rate, R_c, the normalized maximum wall displacement due to the soil creep, $\delta_{ch\max}/H_e$, the creep ratio, R_t, and the total creep ratio, R_t^T.It can be seen from Figure 5(a) that the creep rate decreases nonlinearly with the increasing support stiffness, except for the case of $H/H_e = 0.19$ and the two unusual data points of the $H/H_e = 0.19$ case. At $H/H_e = 0.19$, the creep rate remains nearly unchanged as the support stiffness increases, which is attributed to the fact that the soil creep effect is trivial at a small stress level. The relationship between creep rates at the final

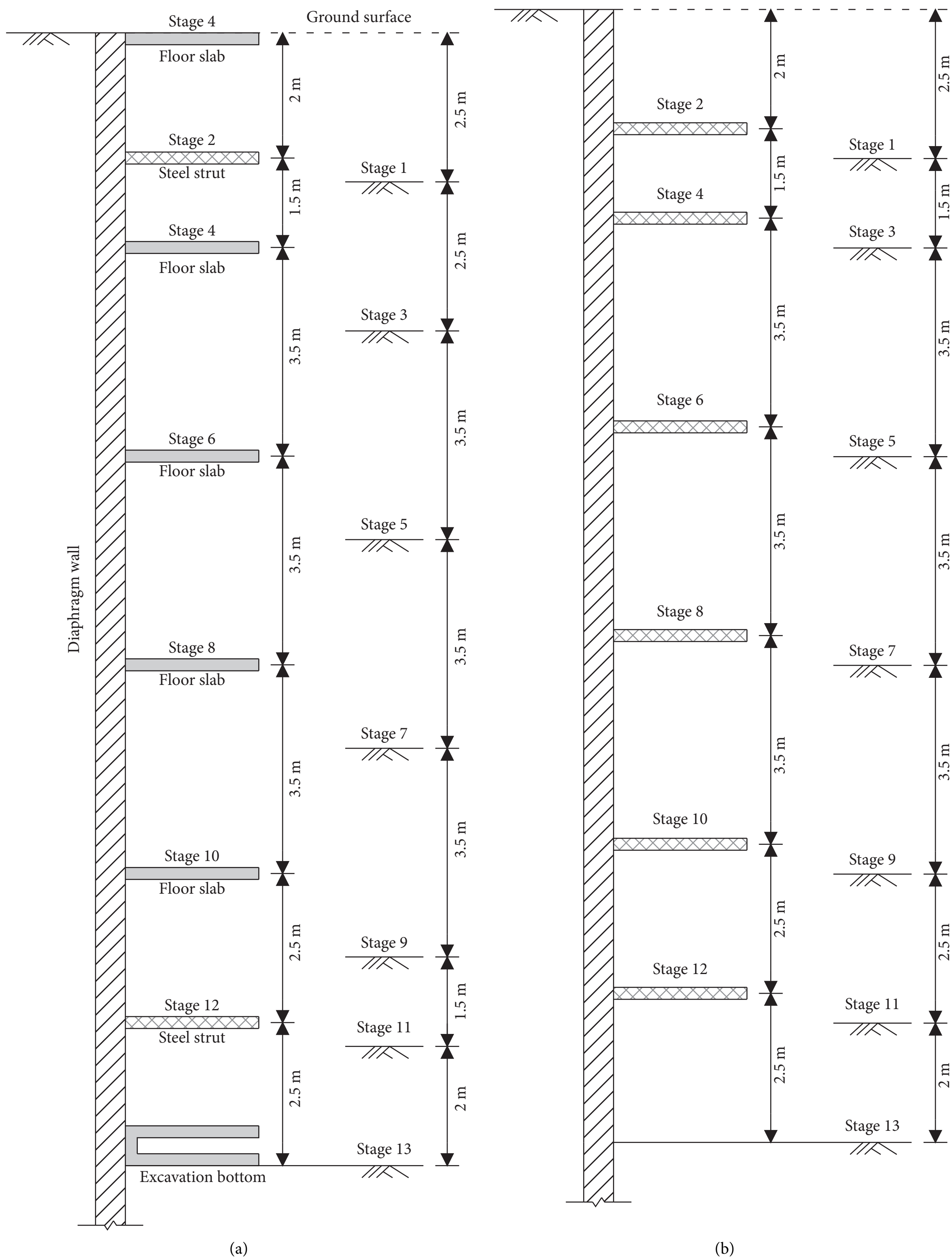

Figure 2: Continued.

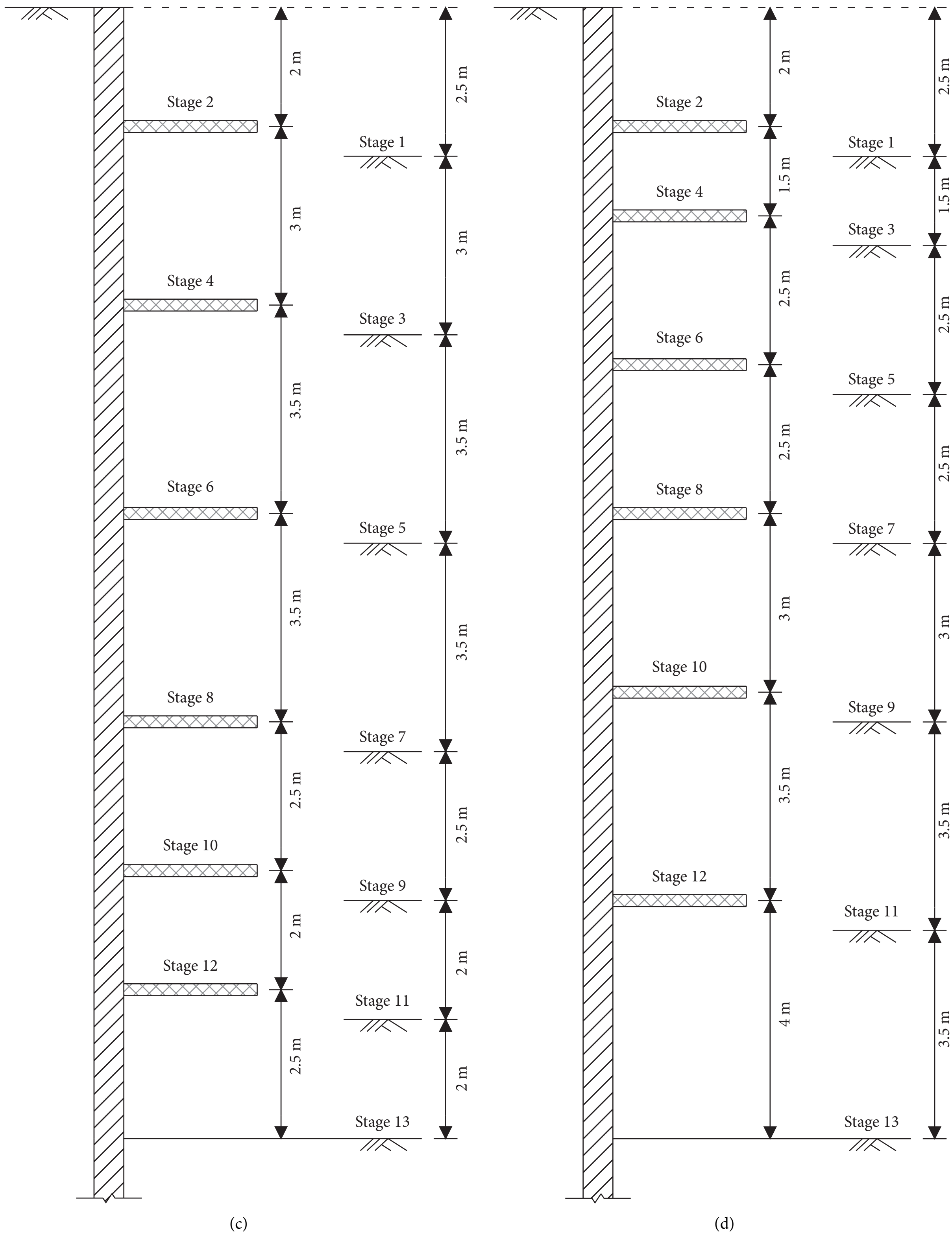

Figure 2: Schematic diagram of the hypothetical deep excavation cases, modified from [32].

excavation depth and support stiffness can be described using an equation $R_{ate} = 0.083 + 161.36/S$. Figure 5(b) indicates a nonlinear decrease in the normalized maximum wall displacement due to the soil creep as the support stiffness increases. This trend may be fitted by $\delta_{ch\max}/H_e = 0.02 + 42/S$ which can be used for estimating the maximum wall

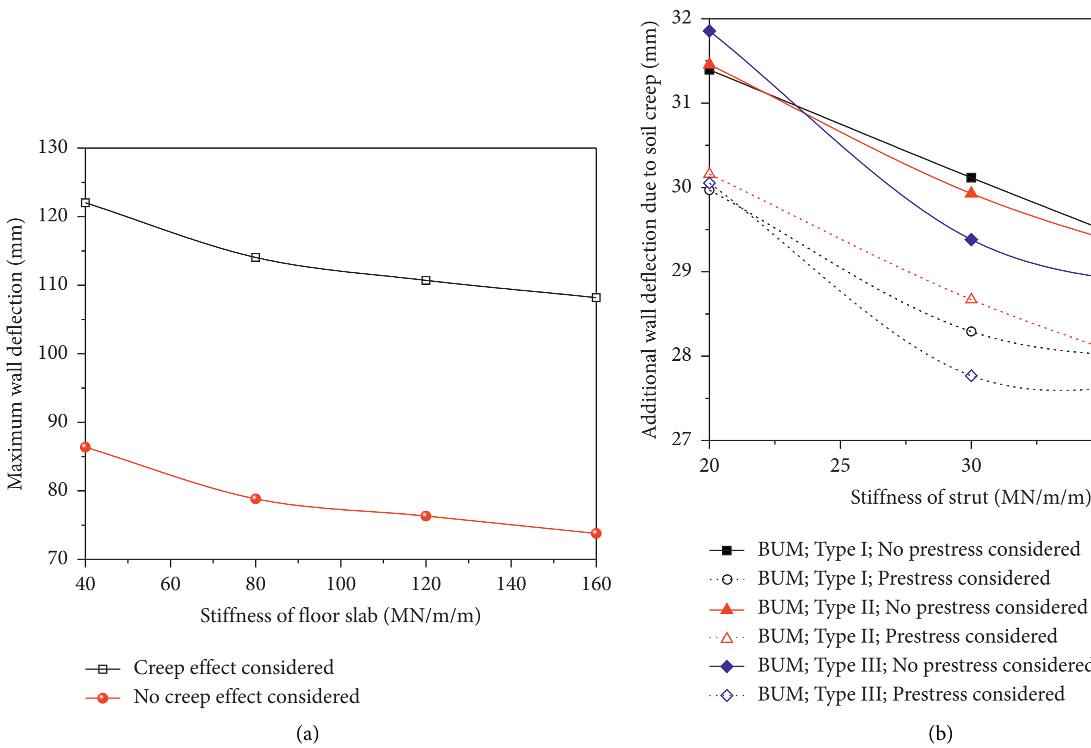

Figure 3: Soil creep effect on wall deflection in cases of (a) TDM; (b) BUM, modified from [32].

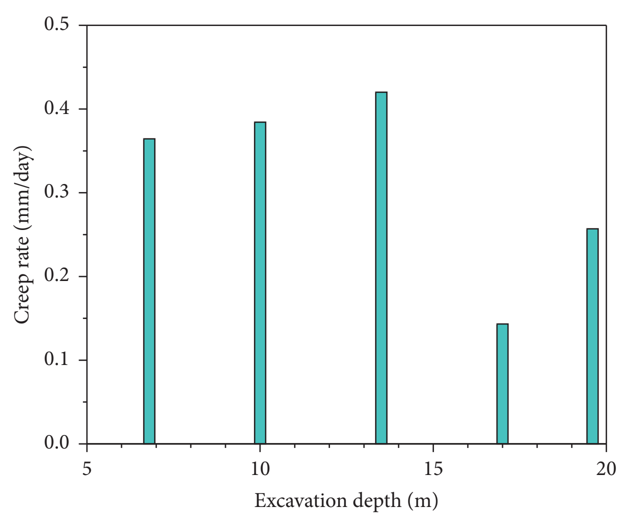

Figure 4: A comparison of creep rates at different excavation depths, modified from [31].

deflection due to the soil creep through two parameters (i.e., the maximum excavation depth and the wall thickness). A threshold of the support stiffness (i.e., $S = 418$), corresponding to a wall thickness of 0.6 m, is observed in Figure 5(c) for the relationship between the creep ratio and the support stiffness. As the support stiffness increases, the rate of the decrease in creep ratio is higher with a greater elapsed time. Figure 5(d) indicates that the total creep ratio decreases linearly as the support stiffness increases until reaching $S = 1350$, and thereafter remains almost unchanged. The total creep ratio at a large support stiffness still accounts for approximately 30% of the maximum wall deflection induced purely by excavation, demonstrating the significance of considering the soil creep effect in accurately estimating the lateral wall movements in soft clay excavations.

3.2. Soil Creep Effect on Ground Movements. The soil creep effect can increase the ground movements around a deep braced excavation. A comparison of the observed and the FEM-calculated time histories of the maximum ground

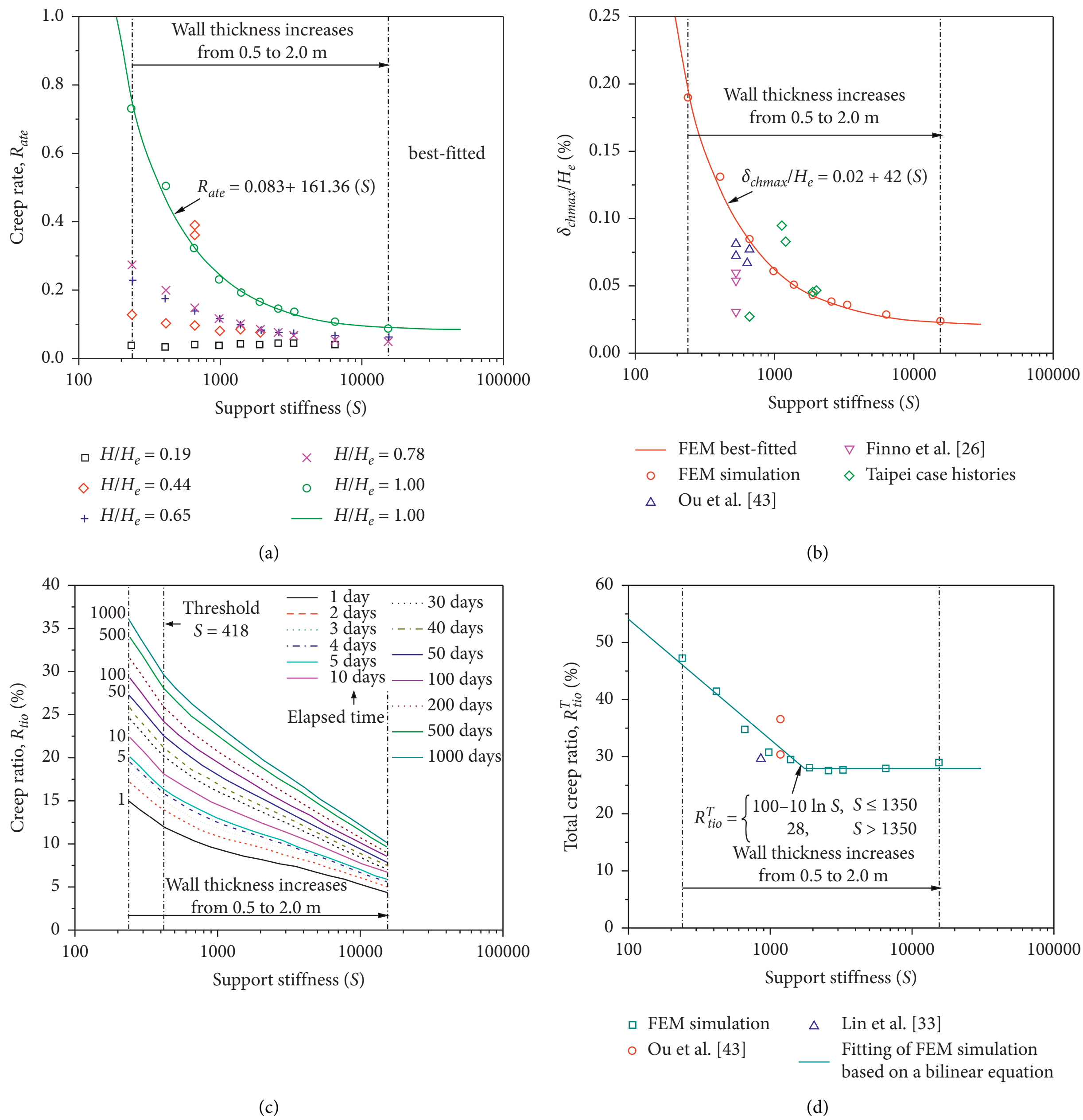

Figure 5: Effects of support stiffness on (a) creep rate, (b) normalized maximum wall displacement due to soil creep, (c) creep ratio, and (d) total creep ratio, modified from [34].

surface settlements around the TNEC excavation project is made in Figure 6(a). In this figure, the numbers 2, 6, 11, 15, 19, 23, and 25 represent, respectively, an excavated depth of 2.8, 4.9, 8.6, 11.8, 15.2, 17.3, and 19.7 m (i.e., maximum excavation depth). In the finite element analysis, two soil constitutive models, which are the soft soil (SS) model and the soft soil creep (SSC) model, have been adopted to generate the FEM-calculated results. The results calculated by the SS model represent the maximum settlements induced by the excavation and consolidation, while the results by the SSC model denote the maximum settlements by the excavation, consolidation, and creep. From Figure 6(a), it can be found that the soil creep effect is neglectable when the excavation depth is less than 8.6 m. Thereafter, the soil creep effect becomes significant, which can be deduced from the good agreement between the results of measurement and the SSC model when the excavation depth exceeds 11.8 m. Quantitatively, the contribution of the soil creep to ground surface settlement increases with time. At the final excavation stage when the maximum excavation depth is achieved, the ground surface settlement contributed by soil creep accounts for almost 57.1% of the total movement.

The time-dependent ground surface settlements induced by the soil creep vary depending on the construction method, support stiffness, and elapsed time among others. Figure 6(b) shows a comparison of the settlement troughs

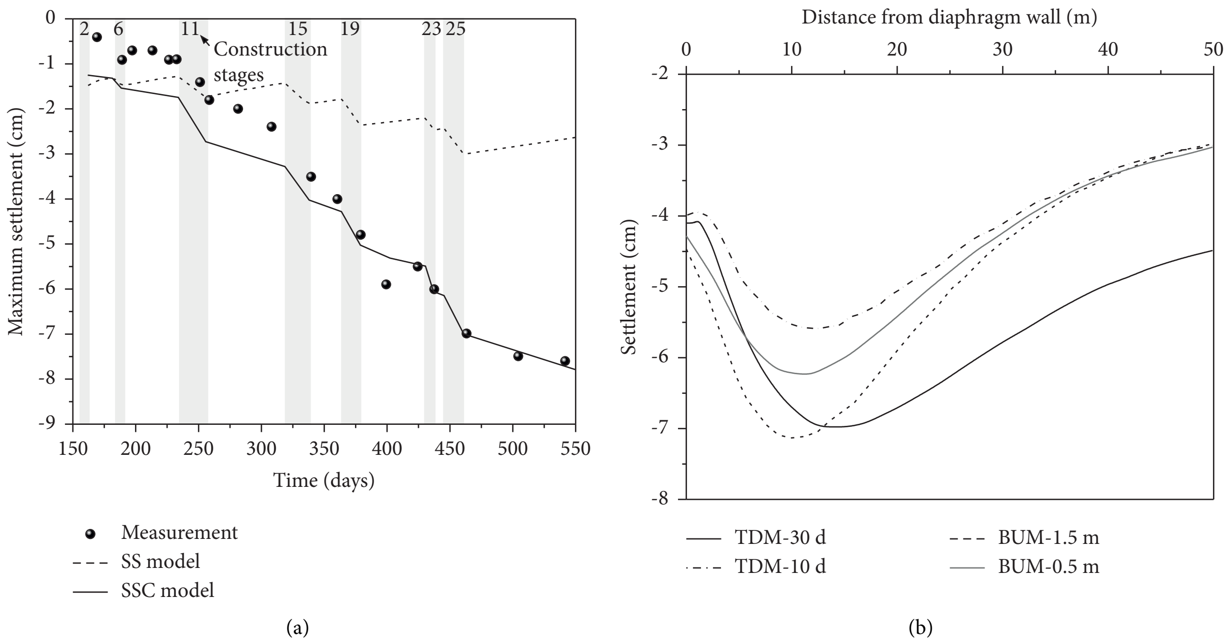

Figure 6: Soil creep effect on ground surface settlements: (a) time-histories of measured and FEM-calculated maximum settlements; (b) comparison of settlement troughs in different cases, modified from [35].

around the excavations constructed using the top-down method (TDM) and bottom-up method (BUM). In this figure, the cases considered have been interpreted in Table 2. By comparing the results of the two cases TDM-10d and BUM-1.5 m in which both the elapsed time and the unsupported length are identical between them, it can be found that the maximum settlement for the top-down method is 0.78 times that for the bottom-up method. This indicates that the stiffer concrete floor in the TDM is more beneficial for restraining soil creep-induced ground surface settlement than the steel strut in the BUM. The maximum settlement in the BUM-0.5 m case is 0.87 times that in the BUM-1.5 m case, demonstrating that an increase in the unsupported length will increase the maximum settlement induced by soil creep. In addition, the maximum settlement in the TDM-10d case is 0.8 times that in the TDM-30d case.

Figure 7 shows a comparison of the ground surface settlements at various construction stages that are obtained by numerical analysis using FLAC and by field observations. The numerical analysis results agree well with the results of field observations for all the considered excavation depths and elapsed times. The elapsed times at the excavation depths of 4.9, 8.6, and 15.2 m, respectively are, 32, 61, and 29 days. According to the field observations, the total settlement induced by the soil creep for these three elapsed times reaches 12.7 mm, which accounts for nearly 16% of the total settlement induced by excavation, consolidation, and soil creep.

In addition to the ground surface settlement, the basal heave for a deep braced excavation is also affected by the soil creep. Based on a 17.4-m-deep braced excavation in Shanghai, a two-dimensional finite element analysis using PLAXIS has been performed by Zhou [44] to investigate the effect of soil creep on the basal heave. The distributions of basal heave against the distance from the excavation center with respect to various excavation depths and elapsed times are shown in Figure 8. The basal heave at $H = 3.6$ m is small with a magnitude of approximately 10 mm. At this excavation depth, the elapsed times of 11 and 25 days produced no significant increase in the basal heave. This may be attributed to the fact the soil creep effect at a small excavation depth is not obvious due to the small magnitude of unloading force. When the excavation depth reaches 9 m, the basal heave induced by soil creep becomes noticeable. At the maximum excavation depth (i.e., 17.4 m), the maximum basal heave due to the soil creep for an elapsed time of 11 days is about 10 mm. In this case, the soil creep effect needs to be considered in the analysis of basal stability for deep braced excavation.

4. Discussion

4.1. Countermeasures for Mitigating Detrimental Effect of Soil Creep. The deformation control of a deep braced excavation is significant for ensuring excavation stability, reducing construction costs, and protecting nearby structures and facilities. In engineering practice, the commonly adopted measures for controlling deformation of excavation are as (1) increasing the embedded depth of the retaining wall; (2) installing walls or piles between excavation and nearby structures [45, 46]; (3) ground improvement; and (4) zoned and staged construction. Moreover, a simple review of the literature as presented in the above sections has indicated that soil creep can induce additional lateral wall deflections, ground surface settlements, and basal heaves. Therefore, the soil creep effect is detrimental to the stability or safety of the excavation and the adjacent infrastructures. However, the countermeasures regarding the soil creep effect on time-

Table 2: Description of the cases considered in Figure 6(b), modified from [35].

Case name	Support structure	Elapsed time	Axial stiffness	Unsupported length (m)
TDM-30d	Concrete floor	30 days	12.9 GPa	1.5
TDM-10d	Concrete floor	10 days	12.9 GPa	1.5
BUM-1.5 m	Steel strut	10 days	4.3 GPa	1.5
BUM-0.5 m	Steel strut	10 days	4.3 GPa	0.5

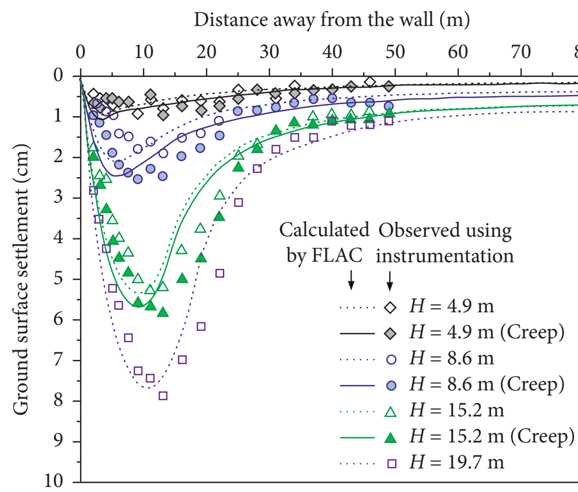

Figure 7: Calculated and observed time-dependent ground surface settlements in the TNEC project, modified from [33].

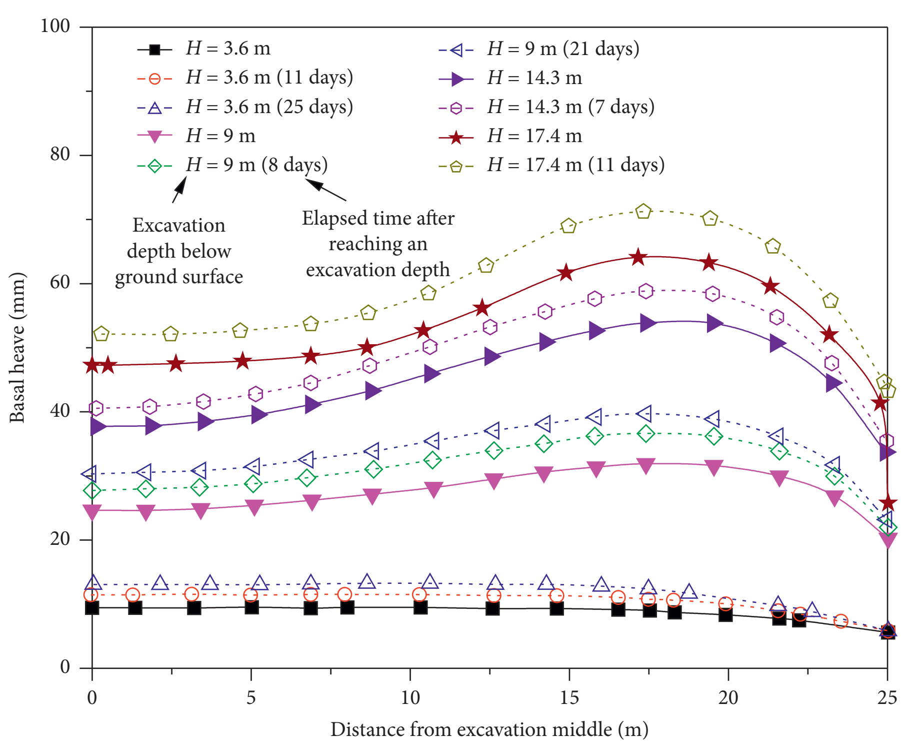

Figure 8: FEM-calculated basal heaves for various excavation depths and elapsed times, modified from [44].

dependent deformation of deep braced excavation have not been well discussed in the literature. Four effective measures are briefly discussed herein.

The first measure is to cast the concrete base slab as soon as possible after excavating to the final depth. By performing plain-strain finite element analysis, Zhou [44] compared the maximum lateral deflections of a retaining pile between the case in which the base slab was cast immediately and the case in which the base slab was cast after 30 days from excavating to the final depth. The results are shown in Figure 9. It can be indicated that timely casting of the concrete base slab can reduce as large as 11.65 mm of maximum deflection of the retaining pile. In addition, in the deep braced excavation with steel struts, it is recommended that prestress of appropriate magnitude should be applied to reduce time-dependent deformation.

The second measure is to select a proper excavation rate. In general, the higher the excavation rate, the smaller the excavation deformation. However, on the one hand, too high excavation rate may induce the collapse of excavation due to the fact that the strength of the concrete slab has not reached 80% of its designed value in such a short period. On the other hand, when the creep of the soil is in the high-speed-creep stage which may be attributed to a high-stress level, an excessively low excavation rate can accelerate the creep failure, which is detrimental to the excavation safety and stability.

The third measure is to reduce the exposure time before installing struts as far as possible. Figure 10 shows a comparison of the lateral deflections of retaining pile at three different moments: (1) the moment of excavating to 13.6 m below ground surface; (2) the moment of 24h past from the first one before installing the struts; and (3) the moment of 24h past from installing the struts. It can be seen that the exposure of 24h before installing struts produces an additional maximum lateral movement of about 5 mm, whereas the effect of exposure of 24h after installing struts is negligible. This trend indicates that strict control of the exposure time before installing struts will be helpful for reducing the time-dependent deformation of deep braced excavation induced by soil creep.

The fourth measure is the zoned and staged construction method developed by Li et al. [47, 48], in which partition walls and/or bipartition walls are constructed to divide an oversized deep excavation into several smaller ones as an excavation group, and then several individual excavations of the excavation group are constructed simultaneously or successively according to the requirement of construction schedule [9, 49]. This construction method follows the temporal and spatial effect appropriately and it is proved to be efficacious in controlling the excavation deformation caused by soil creep through both observation method and numerical simulation method [50, 51].

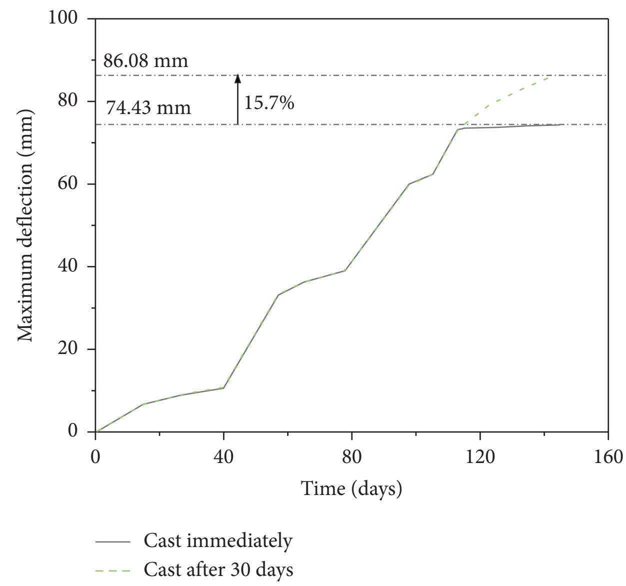

Figure 9: Comparison of maximum deflections between cases of the cast immediately and cast after 30 days from completing excavation, modified from [44].

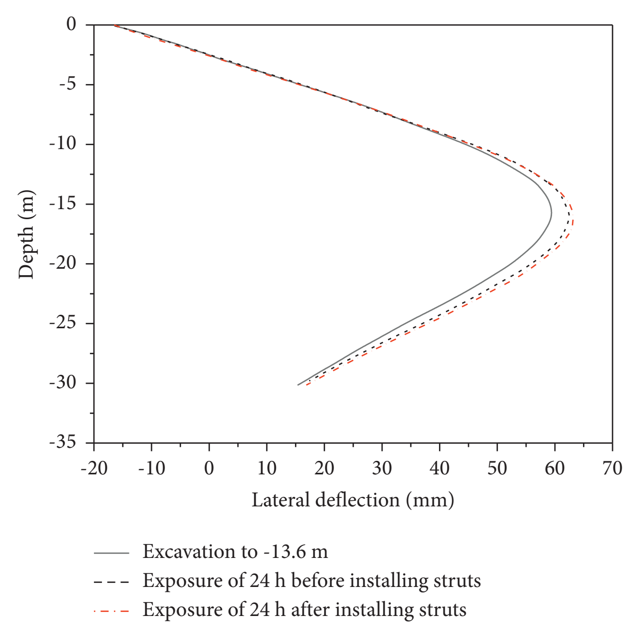

Figure 10: Comparison of lateral deflections of retaining pile between different cases in terms of exposure time, modified from [44].

4.2. Potential Directions of Future Research Work. Existing studies have provided us with some new insights into the effect of soil creep on the time-dependent deformation of deep braced excavation. However, these insights are far from enough for eliminating the detrimental effect of soil creep via optimizing support structure forms and construction procedures. This is because that several important aspects of this topic have not been well understood due to the lack of relevant investigations. Based on the literature review and an in-depth discussion of this issue made among the authors and the other experts in this field, several potential directions of future research work can be recommended for the benefit of both researchers and engineers interested in this topic.

First, centrifuge model tests can be performed to further study the intrinsic mechanism of the soil creep effect and the characteristics of the soil creep effect under different conditions in terms of excavation sequence, ground stratigraphy, support system, etc. Second, it is recommended that the three-dimensional finite element analysis should be carried out to capture the spatial characteristics of the soil creep effect on time-dependent deformation of deep braced excavation. Third, laboratory creep tests following the stress path within the ground around a deep braced excavation may be conducted, and on this basis, a competent stress-strain-time model can be established to facilitate the generation of more accurate results by finite element analysis. Fourth, methods for determining and calibrating parameters of soil creep models need to be further studied and extended considering the accuracy of results and the convenience of application. Finally, the coupling between soil creep and soil consolidation in a deep braced excavation requires further exploration through field observations, experiments, and hydro-mechanical coupled numerical simulations recently reported by Peng et al. [52].

5. Conclusions

A simple review of recent advances in the effect of soil creep on the time-dependent deformation of deep braced excavation has been presented. The methods commonly used for investigating the soil creep effect are described. Lateral wall deflections, ground surface settlements, and basal heaves that are attributed to soil creep are summarized. The primary measures for mitigating the adverse effect of soil creep and the potential directions of future research work on this topic are discussed. On the basis of this literature review, the following conclusions can be drawn:

(1) Field observations and plain-strain finite element analyses are the two dominating methods for this research field. To facilitate the observation of the remarkable soil creep effect and distinguish it from the soil consolidation effect, it is more appropriate to apply the observational method in which the pore-water pressure can be accurately measured to deep braced excavations in soft clays constructed using the top-down method.

(2) The lateral wall deflection due to soil creep can be as large as 30% of the total displacement. The soil creep effect on wall deflection varies depending on many factors such as ground conditions, construction methods, strut or slab stiffness, and workmanship. Three parameters including creep rate, creep ratio, and total creep ratio are generally used to quantify the effect of soil creep on wall deflection. The creep rate decreases nonlinearly with increasing the support stiffness. As the support stiffness increases, the rate of the decrease in creep ratio is higher at a greater elapsed time.

(3) A stiffer concrete floor in deep braced excavation using the top-down method is more beneficial for restraining soil creep-induced ground surface settlement than the steel strut in the case using the bottom-up method. The contribution of soil creep to ground surface settlement increases with time. An increase in the unsupported length will increase the maximum settlement induced by soil creep. The basal heave contributed by soil creep is negligible at a small excavation depth, and becomes observable when the excavation proceeds to a large depth.

(4) To reduce the adverse effect of soil creep, three measures can be adopted in engineering practice: (1) cast the concrete base slab as soon as possible after excavating to the final depth; (2) select a proper excavation rate; and (3) reduce the exposure time before installing struts as far as possible.

(5) Future research work on this topic may include the following several aspects: (1) perform centrifuge model tests to capture the mechanism of this phenomenon; (2) carry out three-dimensional finite element analyses to understand the coupling between soil creep effect and spatial corner effect or soil consolidation effect; (3) conduct laboratory creep tests to improve or establish competent creep constitutive models; and (4) improve the methods of determining and calibrating parameters for the commonly adopted soil creep models [43].

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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