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Basal Heave Stability Analysis of Excavations in Bangkok Soft Clay with Confined Groundwater Recovery Using Numerical Modeling

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Abstract: This study addresses the critical issue of basal heave stability in deep excavations within Bangkok's soft clay, particularly under conditions of confined groundwater recovery. Historical failures in excavation projects highlight the urgent need for effective stability assessments that account for fluctuating groundwater levels. Utilizing a comprehensive dataset derived from case studies and numerical simulations, this research employs the finite element method (FEM) to analyze the interactions between excavation depth, undrained shear strength, and groundwater dynamics. The findings reveal that groundwater recovery significantly influences effective stress, leading to increased uplift pressures that can destabilize excavation support systems. The numerical analyses indicate that Terzaghi's method overestimates safety factors, while Bjerrum and Eide's and Chang's methods closely match numerical results, emphasizing the need for robust analysis that integrates groundwater effects to enhance stability assessments in urban excavations. Grouting techniques applied 10 m below the diaphragm wall significantly improved stability, with safety factors increasing by 63.47%, 87.86%, and 138.72% over various periods. This study contributes valuable insights into excavation design practices and provides empirical data that can inform future research aimed at mitigating hydraulic heave risks in urban environments. Ultimately, the findings advocate for the integration of advanced modeling techniques in geotechnical engineering to improve safety and structural integrity in excavation projects.

Keywords: basal heave; Bangkok soft clay; numerical modeling; groundwater recovery; excavation

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1. Introduction

Basal heave, a critical concern in deep excavation projects, arises due to fluctuating groundwater conditions, particularly during recovery periods. In the context of Bangkok, historical cases have highlighted severe failures associated with excavations and groundwater management [1–3]. Specifically, incidences of basal heave failure underscore the urgency in developing effective stability assessments amid variable hydrogeological conditions. The existing literature reveals that while certain analytical methods have been employed, they do not adequately address the complexities of soil strength variations resulting from groundwater recovery. This deficiency precipitates the central research question: can a robust stability analysis be established for excavations in Bangkok's unique subsoil configuration? This study aims to fill this gap by employing advanced numerical modeling techniques to analyze basal heave stability, thereby contributing critical insights into effective excavation design that accommodates the challenges posed by confined groundwater systems. Basal heave occurs when the upward hydraulic forces due to confined groundwater pressure exceed the weight of the soil above the excavation, potentially leading to catastrophic structural failures if not properly managed. This phenomenon highlights the need for a detailed analysis of factors affecting excavation stability, such as undrained shear strength, excavation depth, and groundwater fluctuations. For example, Do et al. [4] emphasize the critical role of effective stress changes during groundwater recovery periods, indicating that rising water levels can significantly reduce soil stability and increase failure risks. Moreover, Zhang et al.'s [5] work delineates how engineering practices can be refined through a better understanding of progressive failures associated with a basal heave, ultimately underscoring the significance of focused investigations in mitigating risks to urban infrastructure.

Understanding the historical context of basal heave failures in Bangkok construction reveals significant lessons learned from past incidents. Overexploitation of groundwater in the city has led to severe structural failures during excavation, particularly in soft clay layers, underscoring the need for effective management strategies. Notably, the excavation at the Taipei Rebar Broadway is a cautionary tale, illustrating how improperly assessed groundwater levels can result in catastrophic heave failures when basal pressures exceed the soil's bearing capacity [4]. Furthermore, historical data indicate that as groundwater levels fluctuate, the response of excavation stability can vary dramatically, significantly influencing the factors of safety calculated through traditional methods [5]. Consequently, lessons from these failures, especially regarding changes in underground water pressures and their engineering implications, should inform future design protocols, underscoring the necessity for rigorous numerical modeling and comprehensive site investigations to mitigate such risks in ongoing and future projects [6,7]. Rising groundwater levels pose significant challenges to the stability of excavations, particularly in areas with soft clay soils. The recovery of groundwater can induce increased pore water pressure, resulting in reduced effective stress and ultimately leading to potential basal heave failures. The dynamic interaction between groundwater recovery and excavation conditions complicates stability evaluations, as traditional analytical methods may inadequately account for the evolving hydrogeological landscape. Numerical modeling, such as the finite element method, offers a robust framework for simulating these complex behaviors [3]. Nevertheless, the need for detailed analyses remains paramount, as the potential for failure patterns to shift under fluctuating groundwater conditions can yield misleading safety factor assessments. If not adequately addressed, these challenges could undermine the safety and integrity of civil engineering projects in urban environments like Bangkok, exacerbating risks associated with construction in vulnerable geotechnical settings [8].

Considerable attention has been directed toward understanding basal heave failures in soft clay, particularly as they pertain to groundwater recovery scenarios. A synthesis of previous studies reveals a consensus on the critical role that groundwater levels play in destabilizing excavations. Furthermore, the study using finite element methods has corroborated that rising groundwater significantly lowers effective stress, leading to failure mechanisms such as upward heave and sliding surfaces beneath excavations. The relationships have been developed to explain the interplay between soil shear strength, excavation geometry, and artesian pressures, emphasizing that stability is often compromised when groundwater recovery coincides with excavation activities [9]. Notably, studies [4,6,8] have shown that traditional analytical methods tend to overestimate safety factors and inadequately account for the complex behaviors exhibited in soft clay environments, underscoring the need for more nuanced modeling approaches to accurately predict and mitigate basal heave failures.

A comprehensive review of numerical modeling approaches reveals their pivotal role in understanding basal heave phenomena in soft clay areas impacted by groundwater recovery. Various studies [4–9], including those utilizing the finite element method (FEM) and shear strength reduction techniques, underscore the importance of accurately simulating excavation conditions to predict factors of safety (FSs) and failure mechanisms. For instance, the FEM capability to capture complex interactions between groundwater levels and soil behavior indicates that traditional analytical methods often fail to address the non-homogeneous nature of soil profiles. Meanwhile, numerical models demonstrate a nuanced response of ground displacements and heave under varying conditions, as seen in cavity simulations performed. Furthermore, the review encapsulates how these methods refine safety assessments in practical construction scenarios, particularly within the challenging hydrogeological context of Bangkok. As highlighted by Bensmaine et al. [10] and Zhang et al. [11], integrating advanced numerical techniques with empirical observations ensures a robust framework for future excavation projects, reinforcing the necessity for continuous adaptation of modeling approaches in relation to groundwater dynamics. Existing stability analyses in Bangkok often overlook critical factors that contribute to basal heave failures in soft clay, particularly related to groundwater recovery. Current methodologies predominantly employ traditional analytical models that fail to adequately account for the complexities introduced by an anisotropic soil structure and fluctuating groundwater levels. As highlighted in earlier studies, such as the work of Phien-wej et al. [12], the behavior of excavated soils in Bangkok's unique hydrogeological context presents challenges not fully addressed by conventional techniques [13]. Furthermore, the absence of localized empirical guidelines for evaluating safety factors renders these models less reliable in predicting failures, as they do not consider the depth of excavation and variations in soil strength with depth. Consequently, this research seeks to fill these gaps by utilizing a robust finite element modeling approach that integrates varying subsoil conditions and groundwater influences, thus enhancing the predictive accuracy of stability analyses [8]. Jong and Ong [14] present a novel Bayesian network approach for predicting soil–structure interactions during deep excavations. The results indicate that the model accurately predicts soil–structure interactions, even when applied to a geologically different setting. The incorporation of prior knowledge from previous studies enhances the model's performance, particularly in the early stages of excavation. Furthermore, Guo et al. [15] investigated the displacement and force behavior of braced deep excavations under unsymmetrical surcharge conditions. They utilize a finite difference method (FDM), validated against beam-on-elastic-foundation (BEF) calculations and field monitoring data, to analyze the effects of surcharge on diaphragm walls and AM piles. The results demonstrate that unsymmetrical surcharge significantly impacts wall and pile responses, affecting excavation stability.

This study aims to develop a robust numerical model that provides accurate predictions of failure mechanisms and safety factors pertinent to various excavation scenarios, particularly within Bangkok's complex subsoil conditions. By employing the finite element method (FEM), this research seeks to refine the understanding of how parameters like wall embedment depth and undrained shear strength influence stability during groundwater recovery, addressing limitations found in traditional analytical approaches. The anticipated contributions include enhanced guidelines for excavation design practices and the provision of valuable data for future research directed at mitigating hydraulic heave risks. Ultimately, this study aspires to establish a validated methodology that can be adopted for both academic inquiry and field application in urban settings susceptible to groundwater fluctuations.

2. Materials and Methods

2.1. Site Description: The Hydrogeological Context of Bangkok's Subsurface

Bangkok is characterized by a complex hydrogeological setting, significantly influencing excavation stability and management practices in urban development. The city sits atop multiple aquifer systems, including both unconfined and confined layers, with varying degrees of permeability that complicate groundwater flow dynamics. The historical over-extraction of groundwater has led to substantial land subsidence, exacerbating the vulnerability of soft clay layers underlying many construction sites. Current groundwater levels fluctuate as a result of recovery efforts post-pumping, which alters pore water pressures and effective stresses within these soft clays, thereby impacting foundational stability. Understanding these hydrogeological conditions is critical, as evidenced in recent studies that highlights the significant influence of groundwater recovery on basal heave failure mechanisms in excavations. Therefore, a nuanced approach to groundwater management and excavation design that accounts for these hydrogeological complexities is essential to mitigate risks of structural instability in Bangkok's urban landscape [16].

In the context of Bangkok's unique geological and hydrogeological conditions, as shown in Figure 1, the collection of subsoil parameters is paramount for effective excavation stability analyses. A multifaceted approach is necessary, combining techniques like borehole investigations, cone penetration tests (CPTs), and in situ testing to accurately characterize the intricate layering of soil and its mechanical properties. Groundwater dynamics, notably fluctuating levels, significantly influence these parameters, necessitating continuous monitoring to capture changes over time. For instance, the integration of data from the MRT Orange-Line Hua Mak Station's Geotechnical Interpretative Report (GIR) illustrates the critical role of localized data in modeling subsoil behavior under varying groundwater scenarios [17]. Moreover, the utilization of advanced numerical methods, such as finite element modeling, allows for a comprehensive understanding of how various subsoil parameters interact with excavation practices and groundwater recovery [13]. Consequently, an accurate dataset fosters more precise predictions of basal heave failures and enhances construction safety in the region [8].

Understanding groundwater conditions is crucial for assessing basal heave stability in excavations, particularly in urban areas with soft clay-like Bangkok. A comprehensive approach to groundwater data collection can provide valuable insights into how variable groundwater levels impact soil behavior and subsequent excavation stability. Key factors to monitor include groundwater pressure, soil stratigraphy, and the type of aquifers present in the subsoil, as demonstrated in the extensive analyses conducted for the excavation in rock slope stability assessments in various civil engineering projects [18,19]. By integrating the time-series groundwater data, such as those from the aquifer in Bangkok, this study can better predict the effects of confined groundwater recovery on excavation performances. The incorporation of empirical and numerical modeling techniques to quantify these relationships can lead to more reliable designs that mitigate risks associated with potential basal heave failures [20].

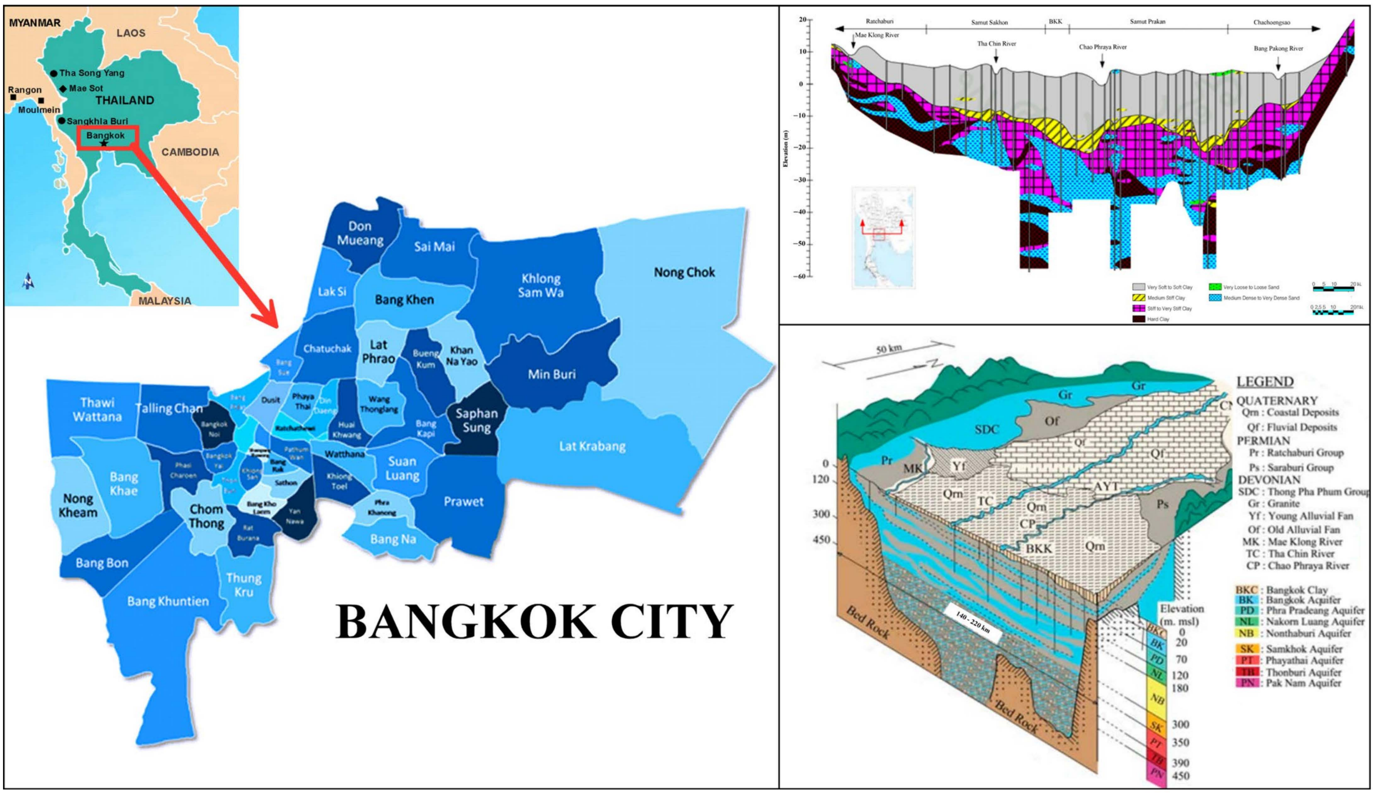

Figure 1. Bangkok aquifer and subsurface information.

2.2. Analytical Method

The analytical methods employed in this study are designed to assess the base stability of excavations by calculating the factor of safety (FS) and examining assumed failure mechanisms. This analysis incorporates equations proposed by notable researchers in the field, specifically Terzaghi's [21], Bjerrum and Eide's [22], and Chang's [23] approaches, as shown in Equations (1), (2), and (3), respectively,

$$\mathrm{FS} = \frac{5.7S_u + 2\alpha S_u D}{\left(\gamma H - \frac{S_u H}{B/\sqrt{2}}\right)} \tag{1}$$

$$\mathrm{FS} = \frac{N_c S_u + 2\alpha S_u D}{\gamma H}, \tag{2}$$

$$\mathrm{FS} = \frac{5.14S_u + S_u H/B + 2\alpha S_u D}{\gamma H}, \tag{3}$$

where S_u is the undrained shear strength of clay, D is the depth of footing, γ is the total density of clay, α is the adhesion factor, H is the depth of excavation, B is the width of considering soil loading on the supports, and N_c is the coefficient depending on the dimensions of the excavation.

Terzaghi's method is foundational in the study of base stability for excavations. It involves an evaluation of the base failure mechanism by considering the interplay of soil properties and load conditions. Terzaghi's equation (Equation (1)) provides a systematic approach to determining the factor of safety, emphasizing the critical role of soil cohesion and internal friction angles in resisting shear stresses. The method developed by Bjerrum and Eide [22] expands upon Terzaghi's framework by introducing additional variables that account for more complex soil behavior under load. Their equation (Equation (2)) incorporates modifications to better predict failure mechanisms in various soil types, particularly considering anisotropic conditions and layered soil structures. This approach allows for a more nuanced calculation of the factor of safety. Chang's method presents an alternative perspective on base failure mechanisms by integrating dynamic factors and load variations over time. Chang's equation (Equation (3)) is particularly relevant for scenarios where external conditions fluctuate, thereby affecting the stability and safety of excavations. This method provides critical insights into time-dependent stability and offers a robust calculation of the factor of safety under transient conditions.

2.3. Numerical Method

Understanding the intricacies of stability analysis in geotechnical engineering necessitates a robust approach, particularly in the context of basal heave failure in soft clay. Numerical modeling facilitates this by introducing finite element methods (FEMs), which allow for detailed simulation of soil behavior under varying conditions. Through sophisticated algorithms, the FEM dynamically adjusts to complex geometry and loading scenarios, capturing the nuances of soil mechanics that traditional analytical methods often overlook. As demonstrated in recent studies, conventional approaches may fail to account for significant variations in soil strength and environmental influences, particularly in the context of groundwater recovery and its associated effects on pore water pressure [24,25]. The finite element approach, as highlighted in Do et al. [4] and Lim and Ou [13], enables a more nuanced understanding of these phenomena, providing critical insights into the development of failure planes and the behavior of retaining walls in deep excavations. Thus, integrating the FEM into the analysis of basal heave stability not only enhances accuracy but also advances the field of geotechnical engineering by addressing complex subsurface interactions effectively.

2.3.1. Development of Conceptual Model

This study employs numerical and analytical methods to conduct a comprehensive base case stability analysis of excavations in homogeneous clay using the properties shown in Table 1. The hardening soil model employed in this study is designed to simulate the geotechnical behavior of excavations under varying groundwater conditions. The model geometry is established as 400 m wide and 100 m deep, as shown in Figure 2a, ensuring sufficient scope to minimize boundary effects. Finer meshes are in layers due to the excavation, which are near loading points or discontinuities, to accurately capture localized deformation. The model convergence involves monitoring the residuals of the governing equations, which represents the imbalance between internal and external forces. The analysis is deemed converged when these residuals fall below a predefined tolerance. The soil's elastic modulus, Poisson's ratio, and yield stress parameters are fundamental and should be determined through appropriate laboratory testing. The shape of the yield surface and the hardening rule, which governs the evolution of the yield surface with plastic deformation, are also critical. The aim is to verify assumptions made in analytical methods, focusing on various conditions influencing basal heave failure. A parametric study investigates factors such as excavation geometry (H/B), undrained shear strength (S_u), depth of hard stratum below the bottom of the cut (T), wall embedment depth (D/H), type of retaining wall, and strutting system.

The simulation addresses excavation scenarios in Bangkok subsoil conditions, utilizing data from the Geotechnical Interpretative Report (GIR). The soil profile includes (1) fill material and a weathered crust 4.5 m thick, overlying a 10.3 m thick Bangkok soft clay layer; (2) medium clay and first stiff clay layers, 1.7 m and 6.06 m thick, respectively; (3) a 6.24 m thick first sand layer interbedded with a 7.0 m thick second stiff clay layer; and (4) subsequent layers, including 19.8 m of second sand and 6 m of third stiff clay, with a third sand layer extending to a depth of 100 m. The conceptual model of the Bangkok subsoil profile is shown in Figure 2b–d.

Table 1. Input parameters for base case stability analysis.

Material/Structure	Parameter	Value
Soft Clay	Saturated unit weight, γ_{sat} (kN/m^3)	15
	Elastic modulus, E (kN/m^2)	$150S_u$–$500S_u$
	Undrained shear strength, S_u (kN/m^2)	10–25
	Interface	1
	Effective cohesion, c' (kN/m^2)	0
	Effective friction angle, $\varnothing'$ (deg)	23
	Poisson's ratio, v	0.2
Concrete diaphragm wall	Axial stiffness, E_A (kN/m)	23.5×10^6
	Bending stiffness, E_I (kN/m^2/m)	2.82×10^6
Steel sheet pile wall	Axial stiffness, E_A (kN/m)	32.95×10^3
	Bending stiffness, E_I (kN/m^2/m)	3.75×10^6
Strut	Axial stiffness, E_A (kN/m)	743×10^3
	Bending stiffness, E_I (kN/m^2/m)	-

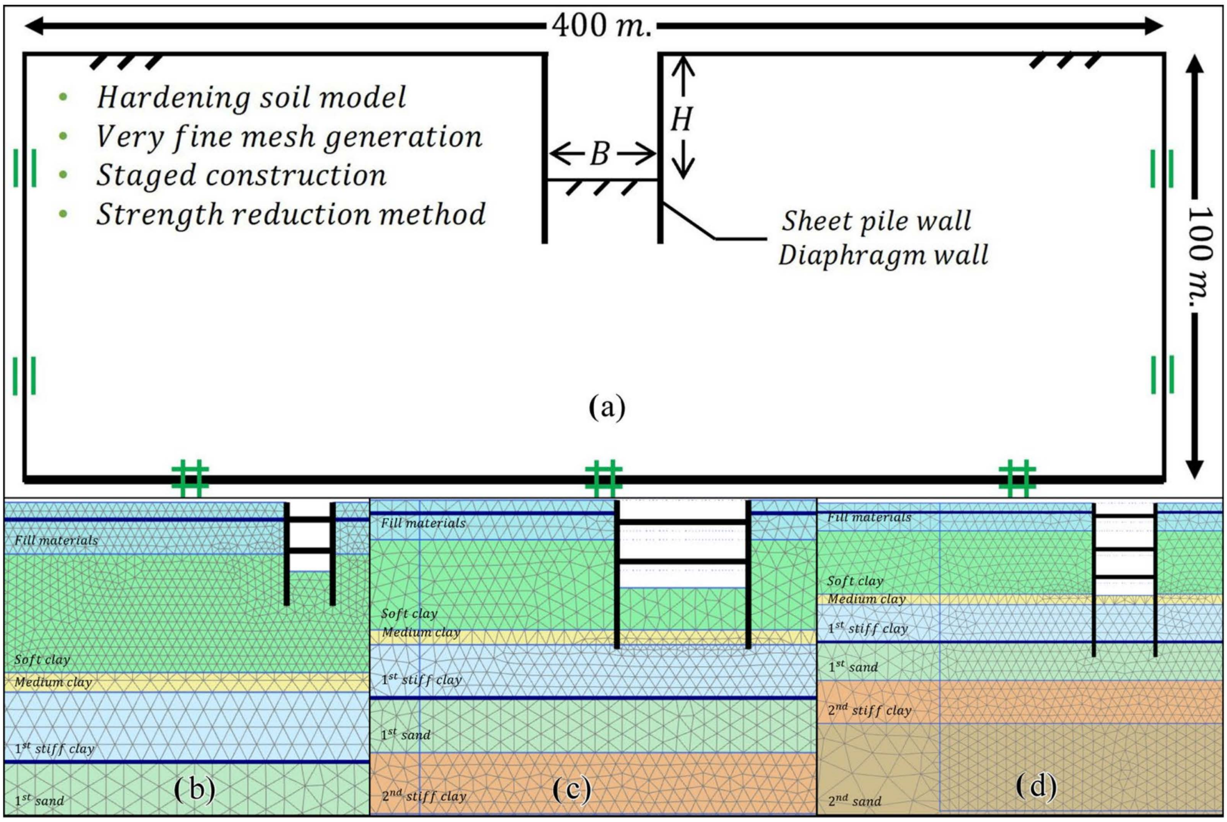

Figure 2. Conceptual model: (**a**) base case, (**b**) free-end sheet pile wall excavation, (**c**) fixed-end sheet pile wall excavation, and (**d**) diaphragm wall excavation.

Input parameters for the hardening soil model were calculated using correlations for Bangkok soil proposed by Pien-wej et al. [12], as shown in Table 2. Three excavation scenarios in Bangkok subsoil conditions were simulated, as outlined in Figure 2b–d. The analysis also investigates the impact of groundwater on excavation stability in the Bangkok subsoil. Groundwater level data, sourced from Saowiang and Giao [26], include measurements from 1960 to 2016, with predictions extending to the 2030s. These data are integral to understanding aquifer behavior and its influence on excavation stability.

Table 2. Input parameter for Bangkok subsoil.

Soil	**Depth (m)**		**Basic Properties**			**Mechanical Properties**							**GW**	**Interface**	**Initial**	
	From	**To**	**Unit Weight (kN/m^3)**	**Soil Model**	**Drainage Type**	E_{50}**(kN/m^2)**	E_{oed}**(kN/m^2)**	E_{ur}**(kN/m^2)**	**m**	$c^{'}$ **(kN/m^2)**	$\varnothing^{'}$ **(deg)**	v_{ur}	K **(m/day)**	R_{inter}	K_0	**OCR**
Fill materials	0	4.5	18.5	Hardening soil	Drained	5000	5000	25,000	0.5	0	25	0.2	8.64×10^{-4}	0.87	0.6	-
Soft clay	4.5	14.8	15	Hardening soil	Undrained	3500	3500	35,000	1	0	23	0.2	8.64×10^{-5}	0.94	0.73	1.6
Medium clay	14.8	16.5	17	Hardening soil	Undrained	6250	6250	62,500	1	5	23	0.2	8.64×10^{-5}	0.8	0.73	1.6
First stiff clay	16.5	22.56	19	Hardening soil	Undrained	19,600	19,600	196,000	0.85	3	25	0.2	8.64×10^{-5}	0.67	0.69	1.5
First sand	22.56	28.8	20.5	Hardening soil	Drained	53,000	53,000	159,000	0.8	0	35	0.2	8.64×10^{-2}	0.44	0.43	-
Second stiff clay	28.8	35.8	20	Hardening soil	Undrained	17,640	17,640	176,400	0.85	20	24	0.2	8.64×10^{-5}	0.55	0.64	1.2
Second sand	35.8	55.6	20.5	Hardening soil	Drained	53,000	53,000	159,000	0.8	0	36	0.2	8.64×10^{-2}	0.4	0.41	-
Third stiff clay	55.6	61.6	20.5	Hardening soil	Undrained	21,840	21,840	218,400	0.85	20	24	0.2	8.64×10^{-5}	0.54	0.64	1.2
Third sand	61.6	80	21	Hardening soil	Drained	55,000	55,000	165,000	0.8	0	36	0.2	8.64×10^{-2}	0.43	0.41	-

2.3.2. Simulations of Numerical Model

The soil is modeled using a 15-noded plane strain triangular element with a hardening soil model. A very fine mesh with local refinement around the excavation area is generated to enhance accuracy in capturing deformation and stress distribution. The excavation is centrally located within the model to prevent boundary interference. Two types of retaining walls are simulated: (1) flexible walls represented by steel sheet pile walls, modeled with an elastic plate element using parameters adopted from Horng [27] and (2) rigid walls represented by concrete diaphragm walls, using parameters from MRT orange-line reports.

Displacement boundary conditions are defined as follows: (1) full fixity at the bottom boundary, (2) no horizontal displacement for side boundaries, and (3) free displacement at the top boundary. Groundwater boundary conditions are specified to include no seepage at the bottom boundary and a seepage boundary at the side boundaries. This study employs PLAXIS 2D for a fully coupled flow-deformation analysis. This analysis investigates the impact of changing groundwater levels on geotechnical properties, considering groundwater pumping in the aquifer from 1960 to 1997 and subsequent recovery from 1997 to 2030. The hardening soil model was selected in this study to represent soil behavior more accurately than simpler models. It incorporates stress-dependent stiffness and soil hardening and distinguishes between primary loading and groundwater rebound behavior. However, the model does not account for time-dependent behavior, which may be a significant factor in groundwater recovery applications.

3. Results and Discussion

A comprehensive analysis of the numerical modeling outcomes reveals critical insights into the mechanisms influencing basal heave stability in excavations subjected to variable groundwater conditions. Notably, the findings indicate that the relationship between groundwater recovery and basal heave behavior exhibits pronounced effects, especially in the context of shallow excavations, as shown by the numerical simulations conducted from 1960 to 2030. As observed, a significant factor of safety increase, approximately 87% during the early drawdown period, was attributed to enhancements in undrained shear strength, affirming the relevance of effective stress principles [5]. In contrast, the results also depict a concerning trend of declining safety factors as groundwater recovers, suggesting a potential for failure mechanisms, particularly in deeper excavations like those represented by diaphragm walls, which demonstrated heightened sensitivity to groundwater fluctuations. Evidence supports that these dynamics necessitate tailored design modifications to effectively mitigate risks associated with basal heave [13]. Hence, it becomes imperative to refine existing analytical frameworks, incorporating the complexities introduced by groundwater behavior to ensure more accurate predictions and enhance excavation stability.

3.1. Comparison of Analytical and Numerical Methods: Factors of Safety

The comparison between analytical and numerical methods for predicting factors of safety (FSs) reveals critical insights into their accuracy and reliability. Figure 3 illustrates notable discrepancies in FS predictions across the various methods for visual analysis. The numerical method results were superimposed on the plots of Bjerrum and Eide’s and Chang’s methods. This overlay highlights a close alignment between the numerical predictions and these two analytical approaches, suggesting their robustness in estimating FSs for basal heave failure in soft clay conditions. Conversely, Terzaghi’s method consistently overestimates the FS. This discrepancy indicates that while the Terzaghi method provides a conservative estimate, it may not accurately reflect the actual stability conditions in soft clay scenarios.

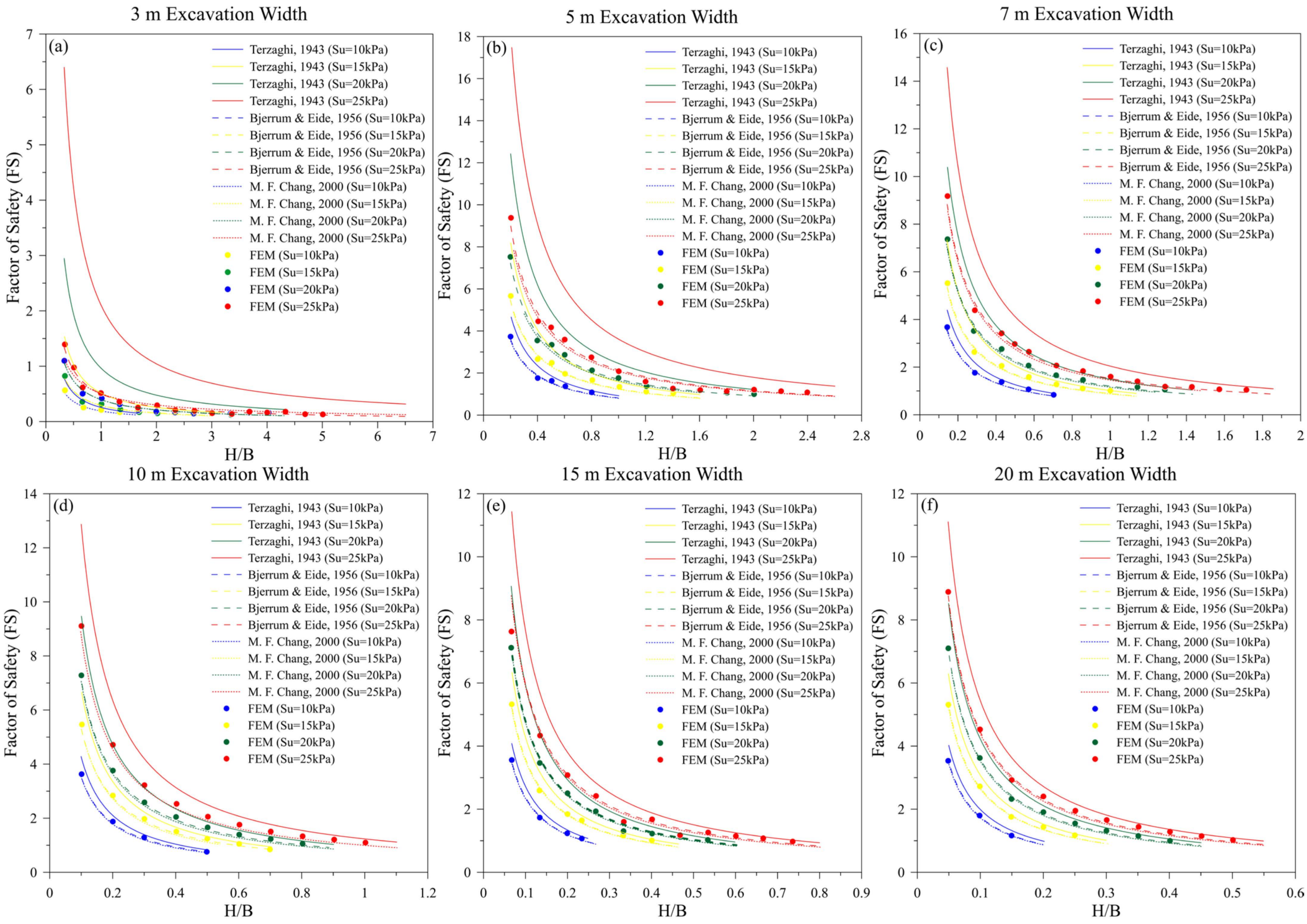

Figure 3. Factor of safety in base case analysis varying with H/B: (**a**) excavation width = 3 m, (**b**) excavation width = 5 m, (**c**) excavation width = 7 m, (**d**) excavation width = 10 m, (**e**) excavation width = 15 m, and (**f**) excavation width = 20 m.

The qualitative assessment underscores the limitations of Terzaghi's method in modern geotechnical applications. Its tendency to overestimate FSs could lead to overly cautious designs, potentially increasing construction costs without proportional safety benefits. In contrast, Bjerrum and Eide's and Chang's methods demonstrate reliability and precision, aligning well with numerical simulations. These approaches integrate more sophisticated soil behavior models, improving their forecast precision for basal heave failure. Overall, the results suggest that while Terzaghi's method provides a conservative FS estimate, Bjerrum and Eide's and Chang's methods are preferable for their accuracy and alignment with numerical findings. These insights are crucial for optimizing design and ensuring safety in excavation projects.

The evaluation of factors of safety in excavation stability has revealed significant disparities between analytical and numerical methods. Numerical approaches, particularly finite element analysis (FEM), provide a more nuanced understanding of stability by intricately modeling soil behavior and groundwater interactions, as demonstrated in Do et al. [4]. Conversely, traditional analytical methods often yield overestimated safety factors, particularly in the context of basal heave stability in soft clay, a pattern evident from comparisons with numerical results. For instance, Terzaghi's method consistently overestimates safety factors, while the methods proposed by Bjerrum and Eide [22] and Chang [23] align more closely with numerical predictions. This discrepancy indicates that while analytical methods offer foundational insights, they may not adequately capture the complexities of real-world conditions, as highlighted by Zhang [28], necessitating the integration of advanced numerical analyses to achieve reliable safety assessments in excavations subjected to variable groundwater conditions.

3.2. Analysis of Failure Mechanisms: Insights from Numerical Modeling

The numerical modeling of failure mechanisms provides valuable insights into the behavior of soil during excavation. By analyzing incremental displacement and deviatoric strain at the final stage of excavation, it can better understand the failure processes. For an excavation with a depth of 2.5 m and a width of 5.0 m (H/B = 0.5), the incremental displacement plots reveal that the soil mass adjacent to the excavation moves downward and flows toward the excavation, as shown in Figure 4. This movement results in the heaving of soil at the base, forming an elastic triangular wedge. The incremental deviatoric strain patterns corroborate this observation, displaying a triangular shear strain configuration and a circular arc beneath the excavation, extending vertically to the ground surface.

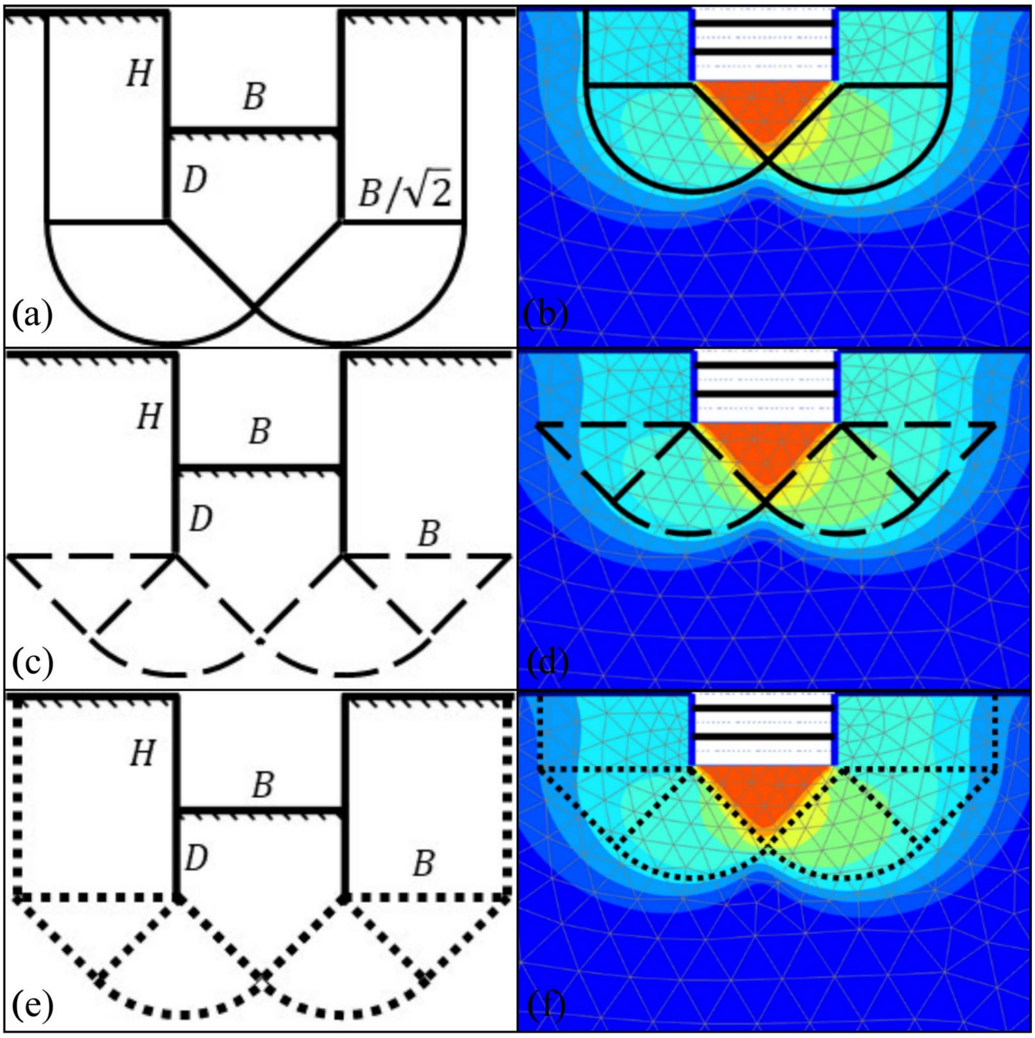

Figure 4. Failure mechanism in base case analysis: (**a**) Terzaghi's [21] failure mechanism, (**b**) failure mechanism comparison between FEM and Terzaghi's [21] failure mechanism, (**c**) Bjerrum and Eide's [22] failure mechanism, (**d**) failure mechanism comparison between FEM and Bjerrum and Eide's [22] failure mechanism, (**e**) Chang's [23] failure mechanism, and (**f**) failure mechanism comparison between FEM and Chang's [23] failure mechanism.

The comparison between the failure mechanisms assumed by different approaches [21–23] and those calculated using the finite element method (FEM) provide critical insights. The failure mechanism assumed by Terzaghi closely aligns with the numerical results, depicting a basal heave failure mechanism composed of a 45° triangular wedge with a circular arc below the excavation. However, the numerical analysis indicates a slightly larger developed failure plane than Terzaghi's original assumption. This suggests that while Terzaghi's model is generally accurate, it may underestimate the extent of the failure plane. The FEM results indicate that the failure plane extends below the excavation and reaches the ground surface, contrasting with Bjerrum and Eide's assumption that the shear strength is not mobilized to the surface for deep excavations. This discrepancy highlights the importance of considering excavation depth, as the observed mechanism pertains to a shallow excavation (H/B = 0.5). Further analysis is required for deeper excavations. The failure mechanism proposed by M. F. Chang aligns precisely with the numerical findings. Chang's assumption of a Prandtl failure surface with a vertical failure plane reaching the ground surface is validated, especially as the vertical failure plane at a distance B from the excavation closely matches the incremental displacement observed in the numerical model. This agreement underscores the accuracy of Chang's model in predicting basal heave failure for shallow excavations.

Understanding the mechanisms behind failure in soft clay excavations is pivotal for improving safety and design methodologies. Insights gained from numerical modeling serve as vital tools in identifying and analyzing these failure modes. For instance, numerical simulations using finite element methods (FEMs) reveal that incremental displacements often exhibit triangular shear strain patterns, diverging from traditional assumptions like those proposed by Terzaghi [21] and Bjerrum and Eide [22]. These numerical analyses also highlight that basal heave failures in shallow excavations involve a failure plane that often reaches the ground surface, contradicting earlier theories that suggested limited mobilization of shear strength. Furthermore, investigations of varying excavation conditions, including groundwater recovery scenarios, provide substantial evidence that the stability of excavations is intricately tied to hydrologic changes, supporting the assertion that analytical methods may not adequately capture the complexities involved in real-world applications [29,30]. Therefore, adapting numerical modeling techniques is crucial for developing more accurate and effective geotechnical design strategies.

3.3. Impact of Excavation Parameters

The analysis of various excavation parameters provides crucial insights into their influence on basal heave failure mechanisms. Figure 5 indicates that for shallow excavations with $H/B \geq 1.0$, a vertical failure plane develops along the excavation depth, and shear strength is mobilized to the ground surface. This observation aligns with the assumptions of Terzaghi [21] and Chang [23]. Even as excavation depth increases to H/B = 2.0, the failure mechanism continues to show slip surfaces reaching the ground surface. This contradicts Bjerrum and Eide's assumption that the shear strength is not mobilized to the surface in deeper excavations. Numerical analysis using the FEM reveals that the basal heave failure mechanism is influenced by the distance of the hard stratum (T), as shown in Figure 6. When T is less than $B/\sqrt{2}$, the failure plane terminates at a hard stratum. This finding is consistent with Terzaghi's and Chang's methods, indicating their methods accurately account for the presence of a hard stratum, while Bjerrum and Eide's method does not.

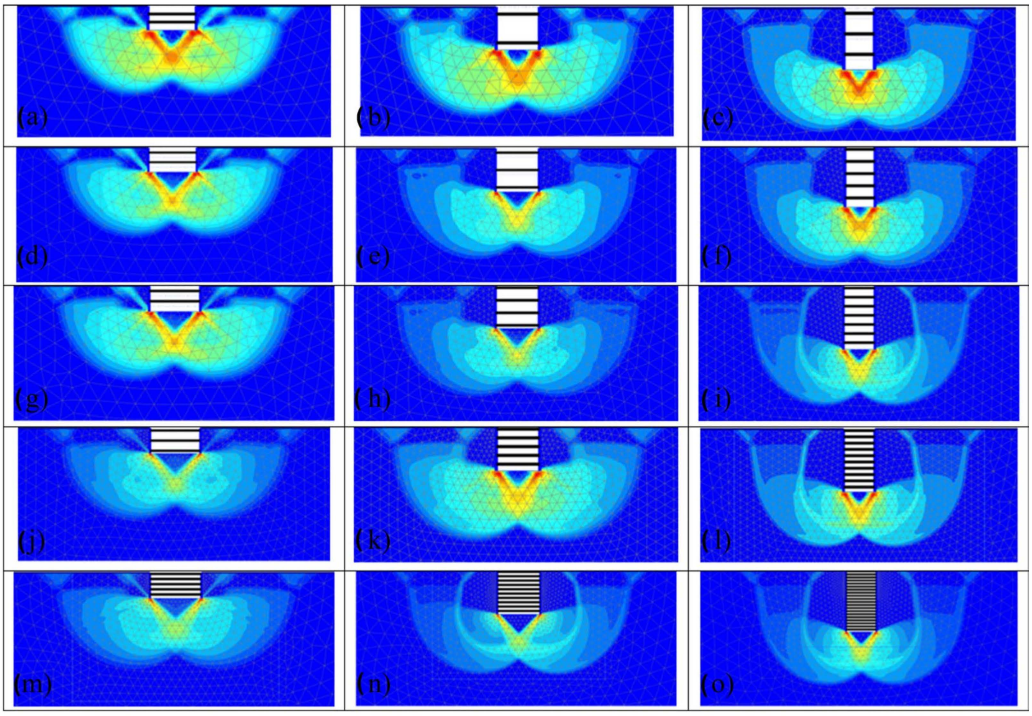

Figure 5. Failure mechanism varying with H/B and excavation depth: (**a**) H/B = 0.5 with excavation depth = 5 m, (**b**) H/B = 1.0 with excavation depth = 5 m, (**c**) H/B = 2.0 with excavation depth = 5 m, (**d**) H/B = 0.5 with excavation depth = 7 m, (**e**) H/B = 1.0 with excavation depth = 7 m, (**f**) H/B = 2.0 with excavation depth = 7 m, (**g**) H/B = 0.5 with excavation depth = 10 m, (**h**) H/B = 1.0 with excavation depth = 10 m, (**i**) H/B = 2.0 with excavation depth = 10 m, (**j**) H/B = 0.5 with excavation depth = 15 m, (**k**) H/B = 1.0 with excavation depth = 15 m, (**l**) H/B = 2.0 with excavation depth = 15 m, (**m**) H/B = 0.5 with excavation depth = 20 m, (**n**) H/B = 1.0 with excavation depth = 20 m, and (**o**) H/B = 2.0 with excavation depth = 20 m.

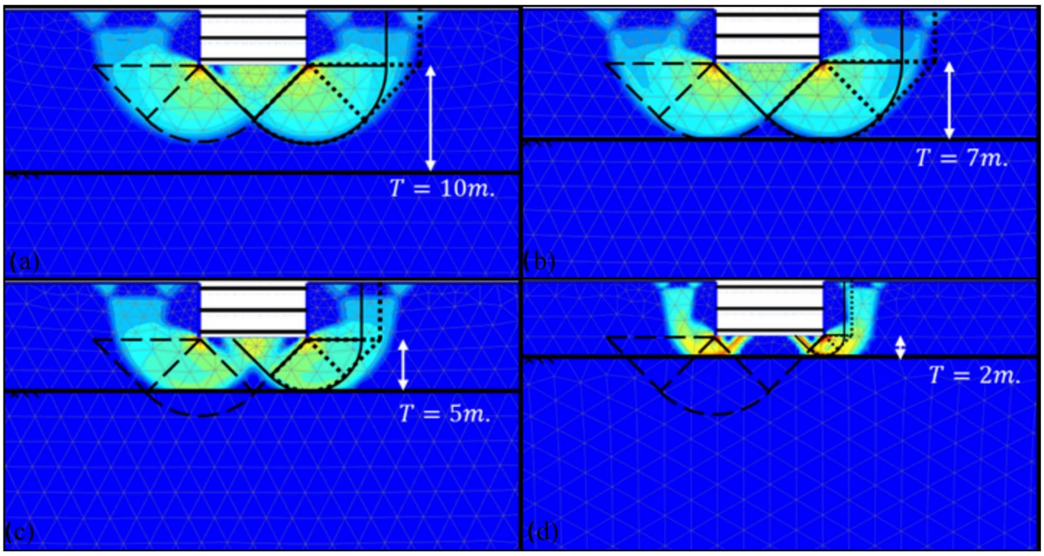

Figure 6. Failure mechanism varying with the distance of the hard stratum: (**a**) T = 10 m, (**b**) T = 7 m, (**c**) T = 5 m, and (**d**) T = 2 m.

In addition, this study varied the undrained shear strength (S_u) from 10 to 25 kPa (Figure 7). The results show that changes in Su have an insignificant effect on the failure mechanism, with only slight variations in incremental deviatoric strain. However, increasing S_u with depth (by 0–2.5 kPa/m) reduces failure plane development, indicating a smaller influence zone, as illustrated in Figure 8. This supports Terzaghi's and Chang's assumptions that mobilization of side shear strength occurs. The impact of wall embedment depth, expressed as a D/H ratio, was investigated in Figures 9 and 10. An optimized D/H ratio of 0.7–1.0, as suggested by Roy et al. [31], significantly increases the factor of safety (Figure 9) against basal heave failure. While the modified Terzaghi's method overestimates FS, the modified Bjerrum and Eide's and Chang's methods closely match numerical analysis results. Increased D/H moves the failure mechanism (Figure 10) from beneath the excavation to below the wall toe, with side shear strength mobilized from the wall tip to the surface.

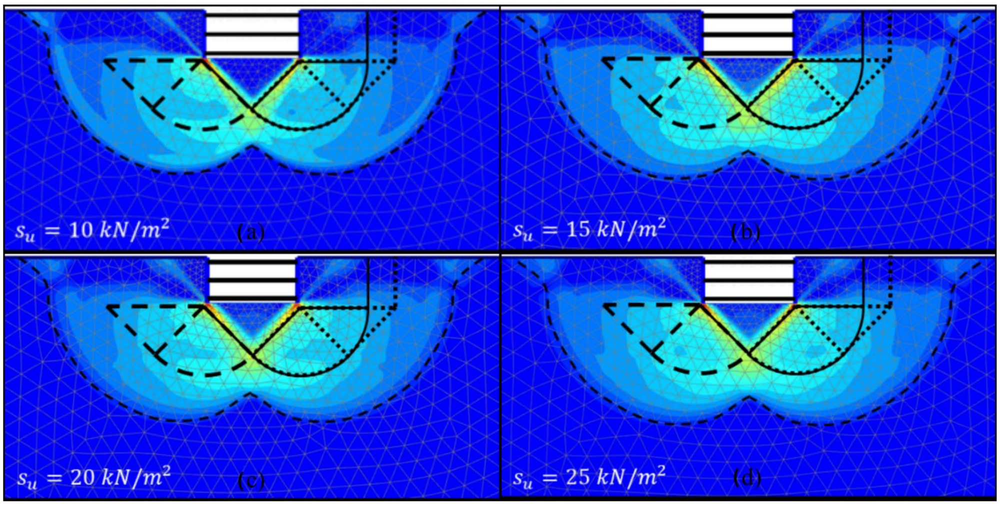

Figure 7. Failure mechanism varying with undrained shear strength: (**a**) S_u = 10 kN/m^2, (**b**) S_u = 15 kN/m^2, (**c**) S_u = 20 kN/m^2, and (**d**) S_u = 25 kN/m^2.

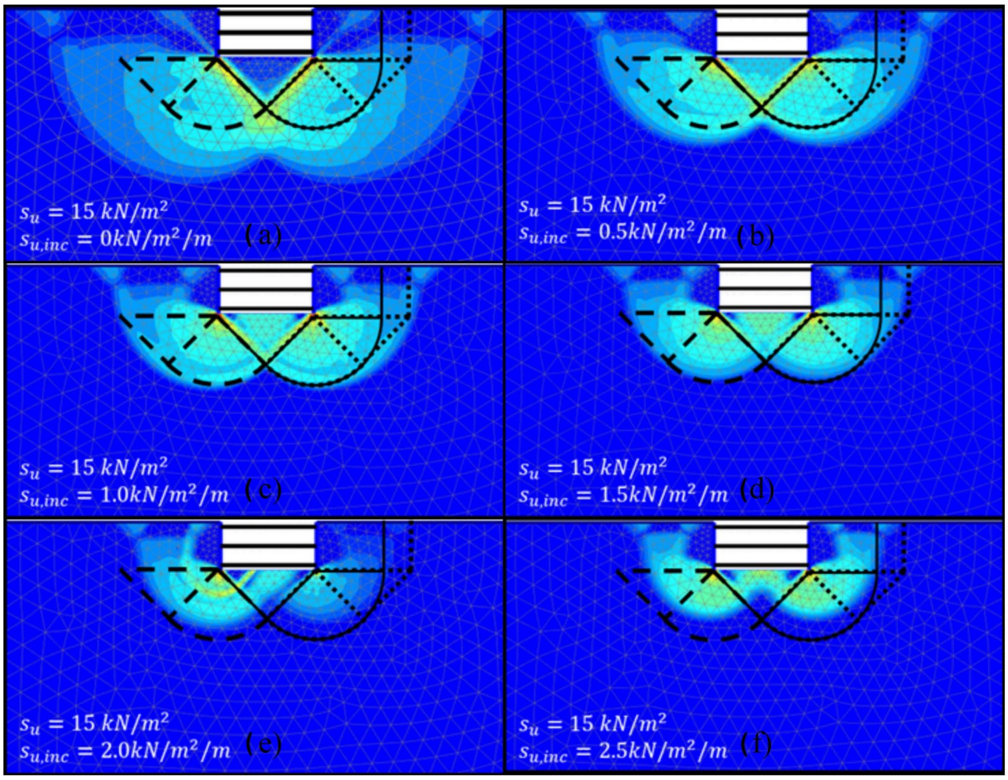

Figure 8. Failure mechanism for undrained shear strength varying with depth: (**a**) $S_{(u,inc)}$ kept constant, (**b**) $S_{(u,inc)}$ = 0.5 kN/m^2/m, (**c**) $S_{(u,inc)}$ = 1.0 kN/m^2/m, (**d**) $S_{(u,inc)}$ = 1.5 kN/m^2/m, (**e**) $S_{(u,inc)}$ = 2.0 kN/m^2/m, and (**f**) $S_{(u,inc)}$ = 2.5 kN/m^2/m.

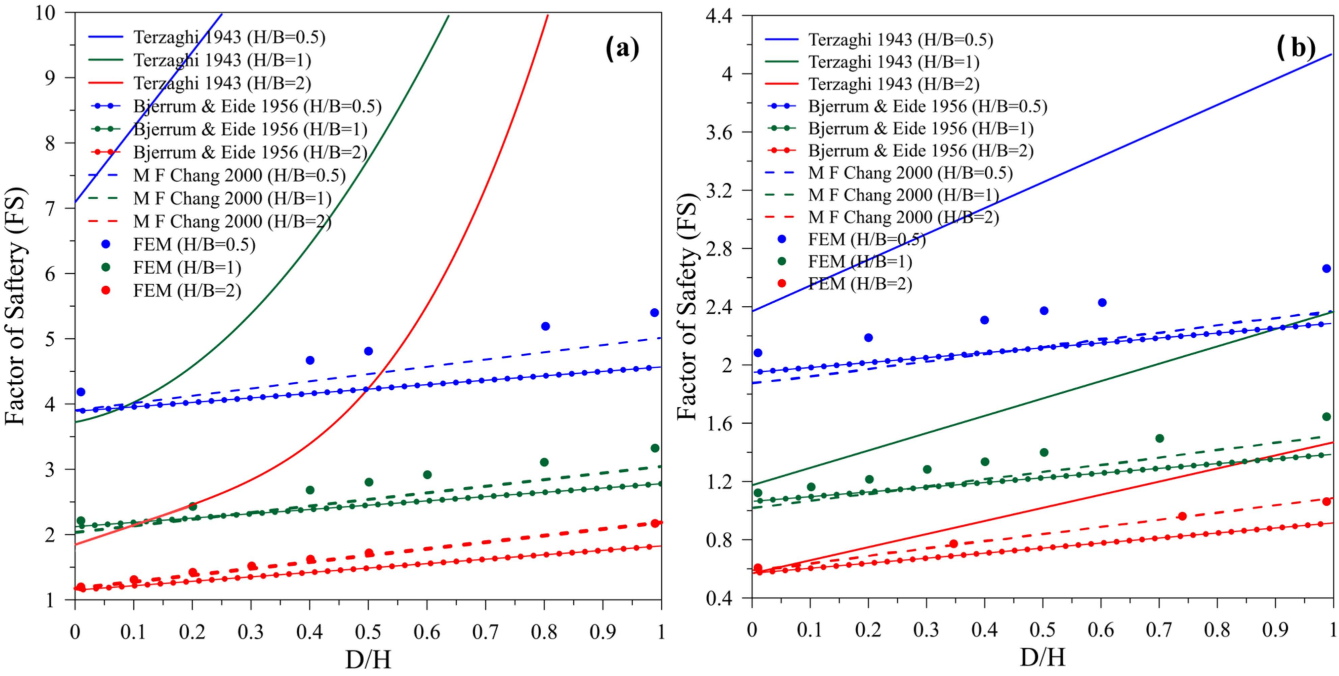

Figure 9. Factor of safety varying with D/H: (**a**) excavation width = 5 m and (**b**) excavation width = 10 m.

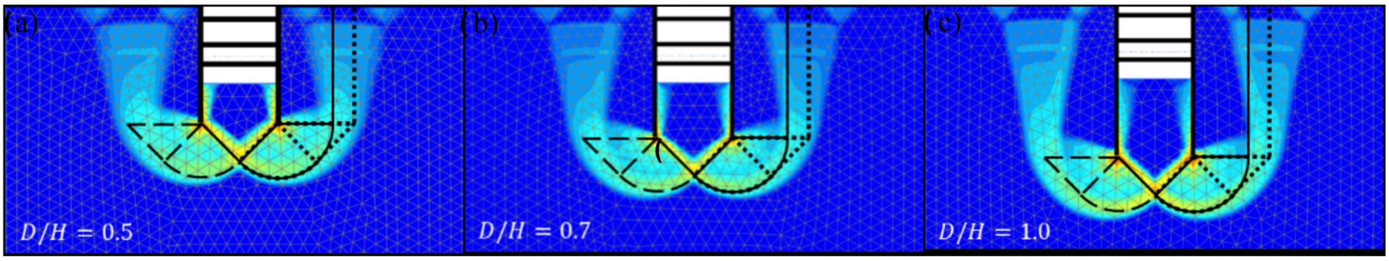

Figure 10. Failure mechanism varying with D/H: (**a**) D/H = 0.5, (**b**) D/H = 0.7, and (**c**) D/H = 1.0.

This study examined the effects of wall stiffness on failure mechanisms, as shown in Figures 9 and 10, comparing flexible steel sheet pile walls and rigid concrete diaphragm walls. The numerical analysis shows that flexible walls result in larger basal heave failure mechanisms due to lower stiffness, while rigid walls, with higher stiffness, reduce failure mechanisms (Figure 9). The analysis of strut levels, ranging from two to fully supported systems, reveals no significant impact on base stability. The factor of safety (Figure 10) remains unchanged across different strut configurations, and failure plane development is consistent, suggesting strut levels do not critically affect basal heave failure for the conditions studied.

The interplay between excavation parameters, such as depth, shear strength, and wall embedment depth, is crucial for evaluating basal heave stability in soft clays with confined groundwater. Increasing excavation depth often leads to greater horizontal displacement and heightened susceptibility to heave, as evidenced by numerical analyses that reveal notable shifts in failure mechanisms, particularly when the excavation depth ratio (H/B) exceeds unity. Moreover, the undrained shear strength (S_u) plays a vital role: as S_u increases with depth, the failure mechanisms exhibit reduced lateral displacements, indicating a positive correlation with stability [32]. Wall embedment depth, represented as a ratio (D/H), further influences the factor of safety, with optimal embedment significantly enhancing resistance to heave. The findings underscore the necessity of incorporating such parameters into design methodologies for excavations, as traditional models frequently overlook these dynamics, leading to conservative or inaccurate safety assessments. Ultimately, a comprehensive evaluation of these excavation parameters is essential to ensure structural stability and mitigate risks associated with basal heave failures.

3.4. Influence of Groundwater Recovery: Effects on Stability and Failure

This study analyzed the stability and failure mechanisms of different excavation scenarios under varying groundwater conditions from 1960 to 2030, using numerical simulations at 5-year intervals. The scenarios included free-end sheet pile walls, fixed-end sheet pile walls, and diaphragm wall excavations, representing shallow, intermediate, and deep excavations, respectively.

- Free-End Sheet Pile Wall Excavation

The numerical analysis indicated that the free-end sheet pile wall excavation in soft clay layers exhibited minimal sensitivity to changes in groundwater conditions, as shown in Figure 11. During the drawdown period (1965–1997), no significant alteration in failure mechanisms was observed. Similarly, during the recovery period (2000–2030), the failure mechanisms remained largely unchanged. However, the factor of safety (Figure 12) increased by approximately 87% from 1960 to 2015 due to enhanced undrained shear strength as pore water pressure decreased. Conversely, the factor of safety decreased by about 22% post-groundwater recovery, as the increasing piezometric pressure reduced the undrained shear strength of the soft clay layer. This suggests that shallow excavations in soft clay layers are relatively unaffected by groundwater fluctuations, corroborating the notion of low sensitivity to such changes.

- Fixed-End Sheet Pile Wall Excavation

In the fixed-end sheet pile wall scenario, the excavation penetrated the first stiff clay layer, with failure mechanisms (Figure 13) aligning with established theories [21,23]. During the drawdown period (1965–1997), the failure plane was constrained at the first sand layer, whereas groundwater recovery (1997–2030) led to the redevelopment of the critical slip surface. The factor of safety (Figure 12) increased by approximately 146% during the drawdown period, remaining relatively stable from 1990 to 2015. However, a 48% decrease was observed from 2015 to 2030 as groundwater recovered to the failure zone. These findings indicate that fixed-end sheet pile wall excavations are more sensitive to changes in groundwater levels, influencing the excavation stability significantly.

- Diaphragm Wall Excavation

The diaphragm wall excavation scenario, representing deep excavations, demonstrated substantial sensitivity to groundwater changes. During the drawdown period (1965–1997), the failure plane (Figure 14) extended deeper and wider through the second stiff clay layer, consistent with Terzaghi [21] and Chang [23]. In contrast, groundwater recovery led to a reduction in the plane's failure due to decreased shear strength. The factor of safety (Figure 12) increased threefold from 1960 to 1997 under drawdown conditions but decreased by approximately 60% during recovery (1997–2030). These results underscore the significant impact of groundwater fluctuations on deep excavations, highlighting their heightened sensitivity to such changes.

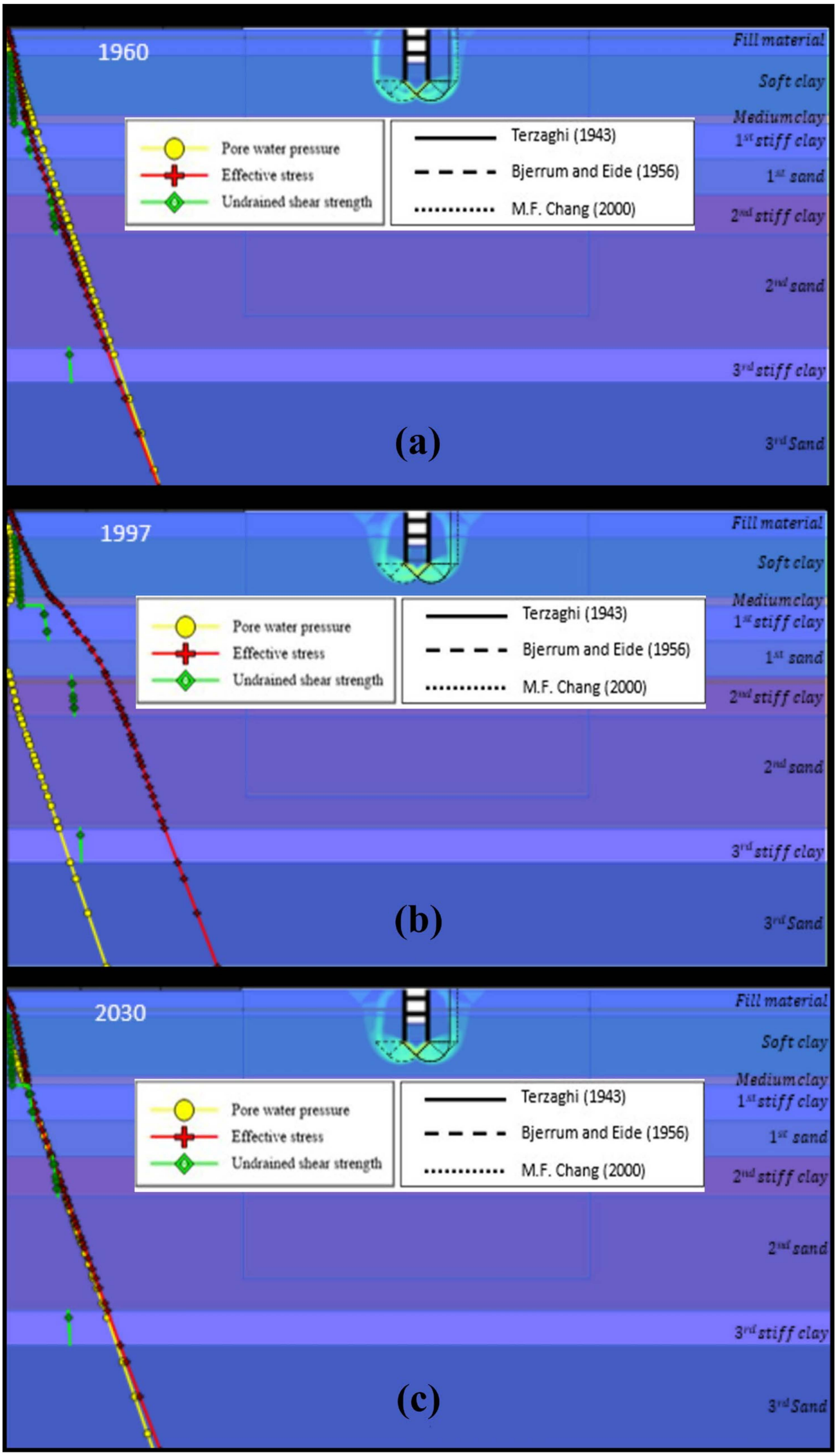

Figure 11. Failure mechanism of free-end sheet pile with groundwater data: (**a**) simulation year 1960, (**b**) simulation year 1997, and (**c**) simulation year 2030.

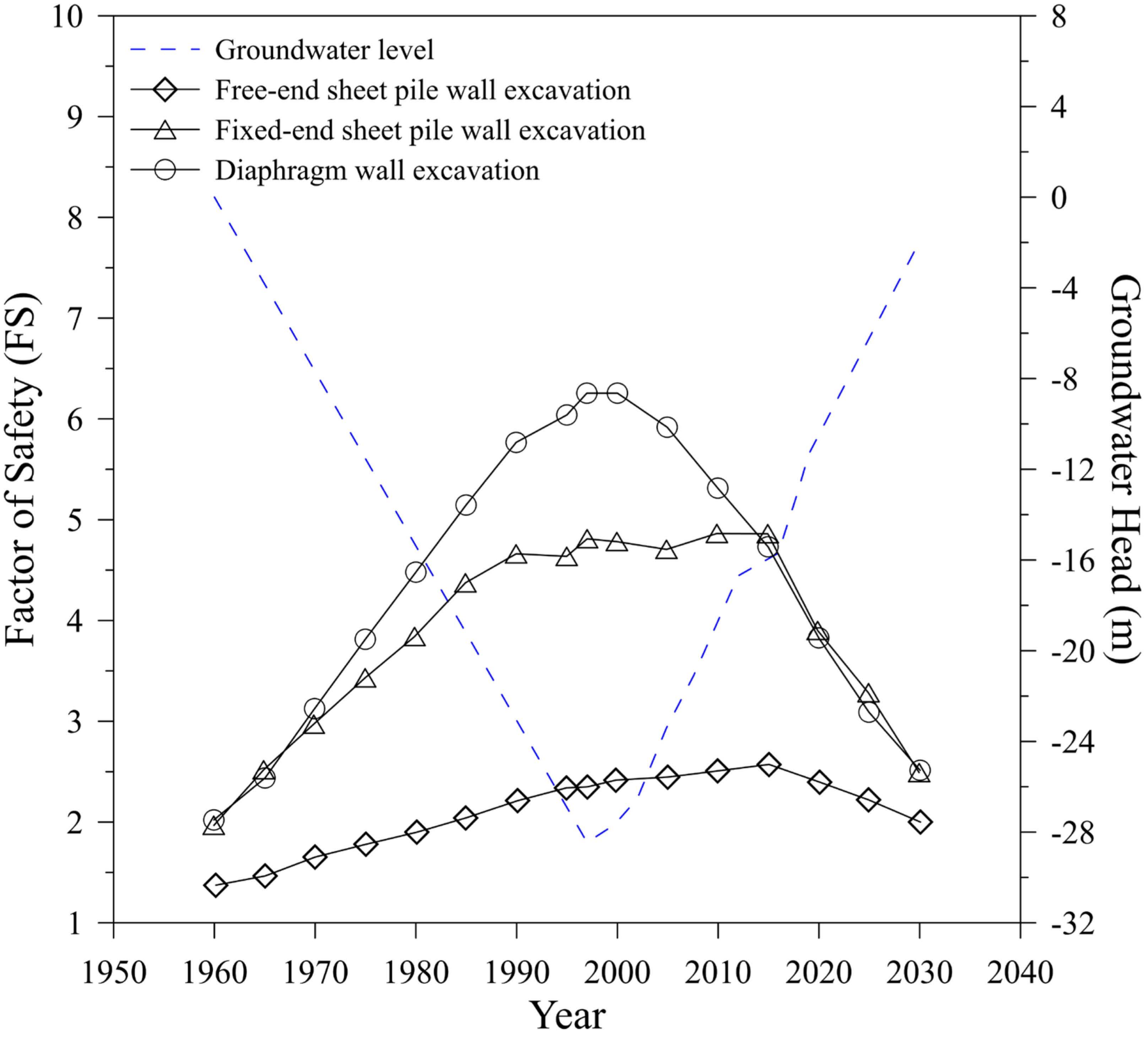

Figure 12. Factor of safety with groundwater changes.

The dynamics of groundwater recovery significantly influence the stability of excavations, particularly in soft clay formations. As illustrated in studies of deep excavations, they are relatively constant, emphasizing a low sensitivity to groundwater changes [3]. Conversely, deeper excavations exhibit heightened susceptibility, where the recovery of pore water pressures can markedly diminish soil shear strength, exacerbating instability [33]. Ultimately, a comprehensive understanding of these phenomena is crucial for anticipating failure and enhancing the structural integrity of excavation sites.

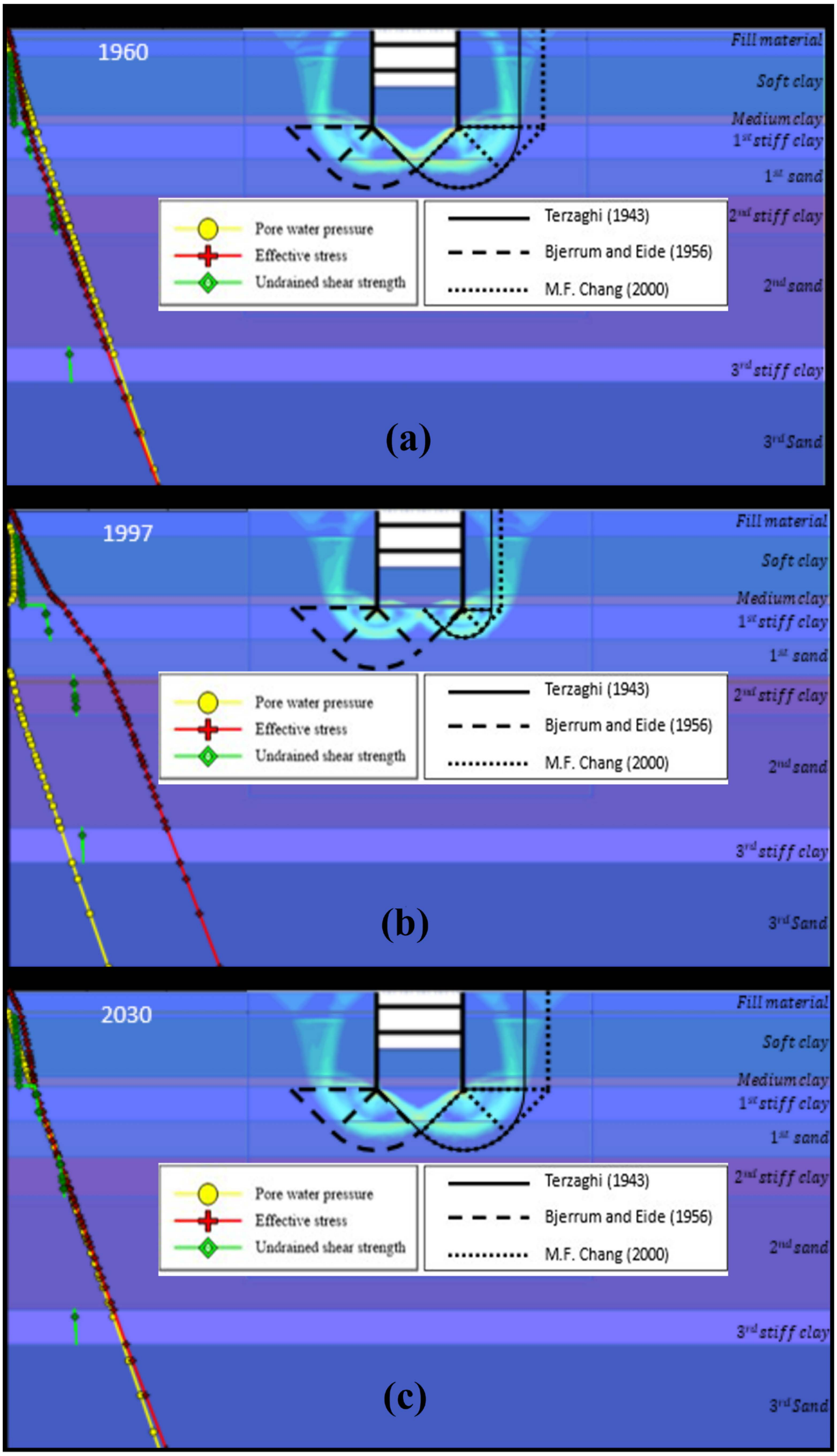

Figure 13. Failure mechanism of fixed-end sheet pile with groundwater data: (**a**) simulation year 1960, (**b**) simulation year 1997, and (**c**) simulation year 2030.

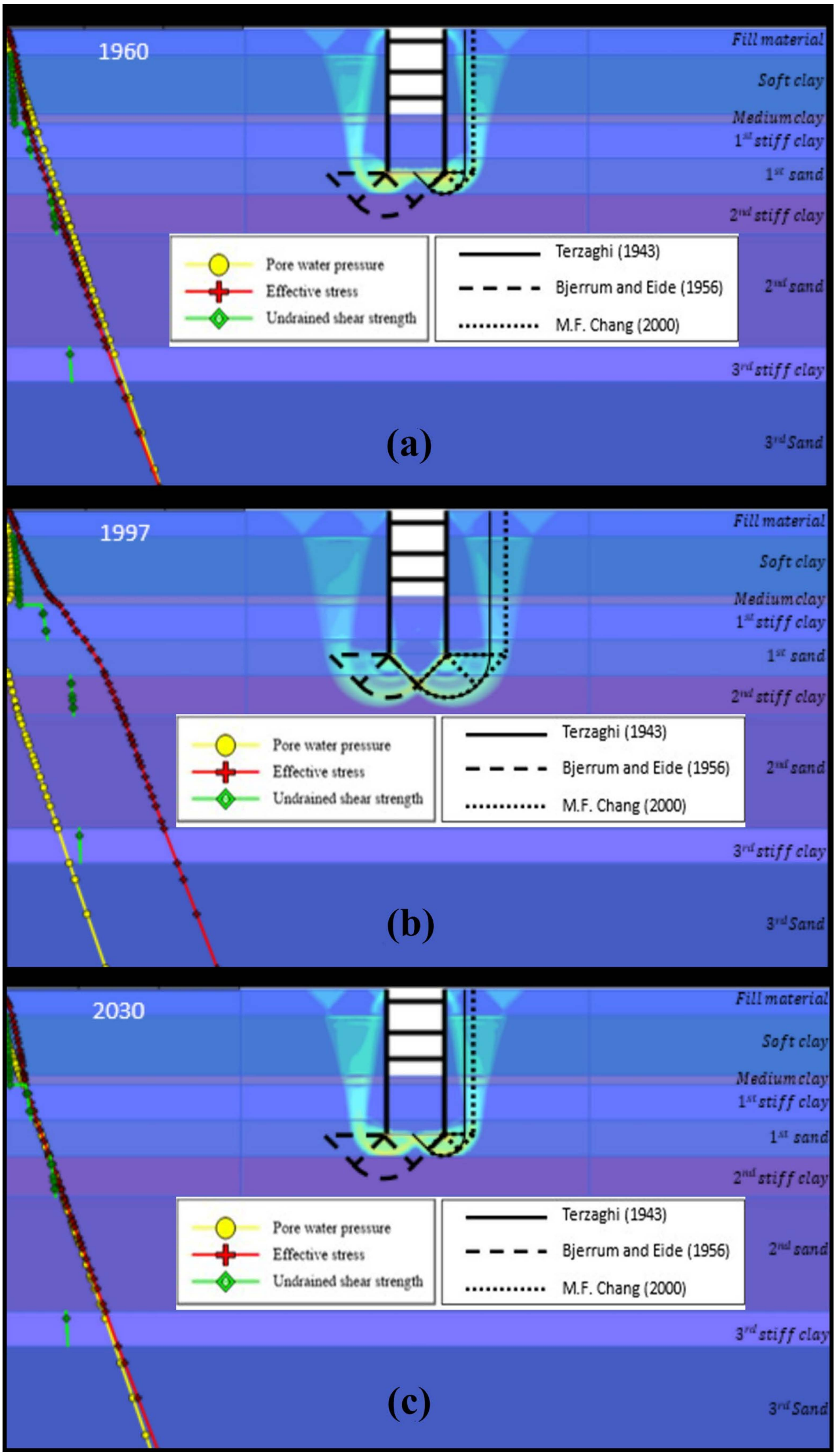

Figure 14. Failure mechanism of diaphragm wall sheet pile with groundwater data: (**a**) simulation year 1960, (**b**) simulation year 1997, and (**c**) simulation year 2030.

4. Case Study: Basal Heave Failure Analysis at MRT Orange-Line Hua Mak Station

The construction of the MRT Orange-Line Hua Mak Station in Bangkok presented complex geotechnical challenges (Table 3), particularly concerning basal heave failure. This case study aims to assess the base stability analysis conducted during the station's construction in 2019. The analysis utilized both analytical and numerical methods to simulate realistic excavation behaviors. The stability analysis involved a comprehensive numerical model, designed to replicate the sequential excavation process accurately. The model's validity was assessed by comparing its simulation results with actual lateral wall movement data from inclinometers installed in the diaphragm wall. The diaphragm wall, a critical structural component, had a thickness of 1.2 m and extended to a toe level 38.5 m below the ground surface. Basal stability was analyzed using several methods, including Terzaghi's method, Bjerrum and Eide's method, Chang's method, and the FEM. The station's structural elements were considered, including a 1.2 m thick roof slab, a 1.0 m mezzanine slab, a 1.2 m concourse slab, and a 1.8 m base slab. The excavation was modeled under staged construction conditions with simulated groundwater levels, utilizing a fully coupled flow-deformation method and the Head function for calculations.

Table 3. Input parameters for MRT Orange-Line Hua Mak Station.

Material/Structure	Parameter	Value
Concrete Diaphragm wall	Axial stiffness, E_A (kN/m)	23.5×10^6
	Bending stiffness, E_I (kN/m^2/m)	2.82×10^6
	Level (m)	38.5
Roof slab	Axial stiffness, E_A (kN/m)	24.8×10^6
	Bending stiffness, E_I (kN/m^2/m)	17.1×10^6
	Level (m)	3.85
Mezzanine slab	Axial stiffness, E_A (kN/m)	6.04×10^6
	Bending stiffness, E_I (kN/m^2/m)	8.85×10^5
	Level (m)	9.55
Concourse slab	Axial stiffness, E_A (kN/m)	7.25×10^6
	Bending stiffness, E_I (kN/m^2/m)	9.88×10^5
	Level (m)	15.75
Base slab	Axial stiffness, E_A (kN/m)	50.4×10^6
	Bending stiffness, E_I (kN/m^2/m)	13.6×10^6
	Level (m)	22.9
Grout in sand	Unit weight, γ (kN/m^3)	21
	Drainage type	Undrained
	Effective elastic modulus, E' (kPa)	300,000
	Undrain shear strength, S_u (kPa)	500
	Hydraulic conductivity, K (m/day)	5.13×10^{-10}
Grout in clay	Unit weight, γ (kN/m^3)	17
	Drainage type	Undrained
	Effective elastic modulus, E' (kPa)	100,000
	Undrain shear strength, S_u (kPa)	300
	Hydraulic conductivity, K (m/day)	5.13×10^{-10}

The simulation results (Figure 15) aligned closely with monitored wall deformation data, demonstrating the model's accuracy. However, at the base level, the model overestimated the deformation magnitude. Despite this, the lateral wall movement profile maintained good agreement. The basal heave failure mechanism was observed to develop fully in the second sand layer with vertical side shear strength mobilizing to the ground surface, consistent with Terzaghi's and Chang's assumptions. Conversely, Bjerrum and

Eide's assumptions were not applicable. The factor of safety against basal heave failure was analyzed, revealing that Terzaghi's method overpredicted the safety factor, while Bjerrum and Eide's and Chang's results closely matched numerical analysis. For future scenarios in 2025 and 2030, the analysis anticipated reduced basal heave failure as groundwater levels increased. However, the calculated safety factor decreased by 18.69% and 39.36%, respectively. The following two grouting strategies were examined:

- Slab grouting: a 4 m thick slab grouting at the diaphragm toe significantly increased the factor of safety by 34.10% in 2019, 45.52% in 2025, and 72.97% in 2030, as shown in Figure 16;
- U-shape grouting: applied 10 m below the diaphragm wall toe, it altered the failure mechanism, with safety factors increasing by 63.47%, 87.86%, and 138.72% over the same periods, indicating substantial improvement in stability and mitigation of groundwater impact, as shown in Figure 17.

The findings reveal that basal heave failure mechanisms predominantly developed within the second sand layer, mobilizing vertical side shear strength to the ground surface and necessitating robust analysis that integrates groundwater effects to enhance the accuracy of stability assessments in such urban excavations [34]. The MRT Orange-Line Hua Mak Station's basal stability analysis demonstrated the efficacy of combining analytical and numerical methods, validated through extensive monitoring. The construction of the MRT Orange-Line Hua Mak Station in 2019 followed a carefully planned sequence of seven stages, designed to ensure structural integrity and minimize ground disturbance. The process began with the installation of diaphragm walls (D-walls) and barrette piles, complemented by stanchion placement to provide temporary support. Subsequently, an initial excavation of approximately 2.5 m was conducted, followed by the installation of temporary struts to maintain lateral stability. The construction then progressed in a top–down manner, with each level being excavated and its corresponding slab constructed before moving to the next lower level. This sequence included the roof level, mezzanine level, concourse level, and base level. The final stage involved the construction of permanent columns, removal of temporary stanchions, and backfilling to ground level. Throughout this process, wall deflection was closely monitored to assess the structural behavior and ensure the safety and stability of the excavation. These monitoring data provided valuable insights into the performance of the support system and the overall excavation process, allowing for real-time adjustments if necessary and contributing to the body of knowledge in deep excavation practices in urban environments.

To validate the proposed numerical model, a comparative analysis was conducted between the model-estimated wall deflections and the actual monitoring data obtained during the excavation process. This validation exercise was crucial for assessing the accuracy and reliability of the numerical model in predicting the structural behavior of the excavation support system. The comparison revealed a close correlation between the calculated wall deformations and the observed monitoring data across multiple excavation levels, demonstrating the model's efficacy in simulating real-world conditions. However, it is noteworthy that at the base level, the model exhibited a tendency to overestimate the magnitude of deformation. Despite this discrepancy at the deepest excavation stage, the overall lateral wall movement profile maintained good agreement with the monitoring data. This consistency across most excavation levels suggests that the proposed numerical model provides a reliable framework for predicting wall deflections in deep excavations, although with some limitations at extreme depths. The validation results (Figure 18) underscore the model's potential as a valuable tool for design and analysis in similar geotechnical projects while also highlighting areas for potential refinement in future studies. This study highlighted the importance of accurate modeling in predicting basal heave failure and emphasized the substantial stabilizing effect of grouting techniques. Future excavations must consider groundwater recovery's impact on stability, with grouting providing a reliable solution for enhancing safety against basal heave failure.

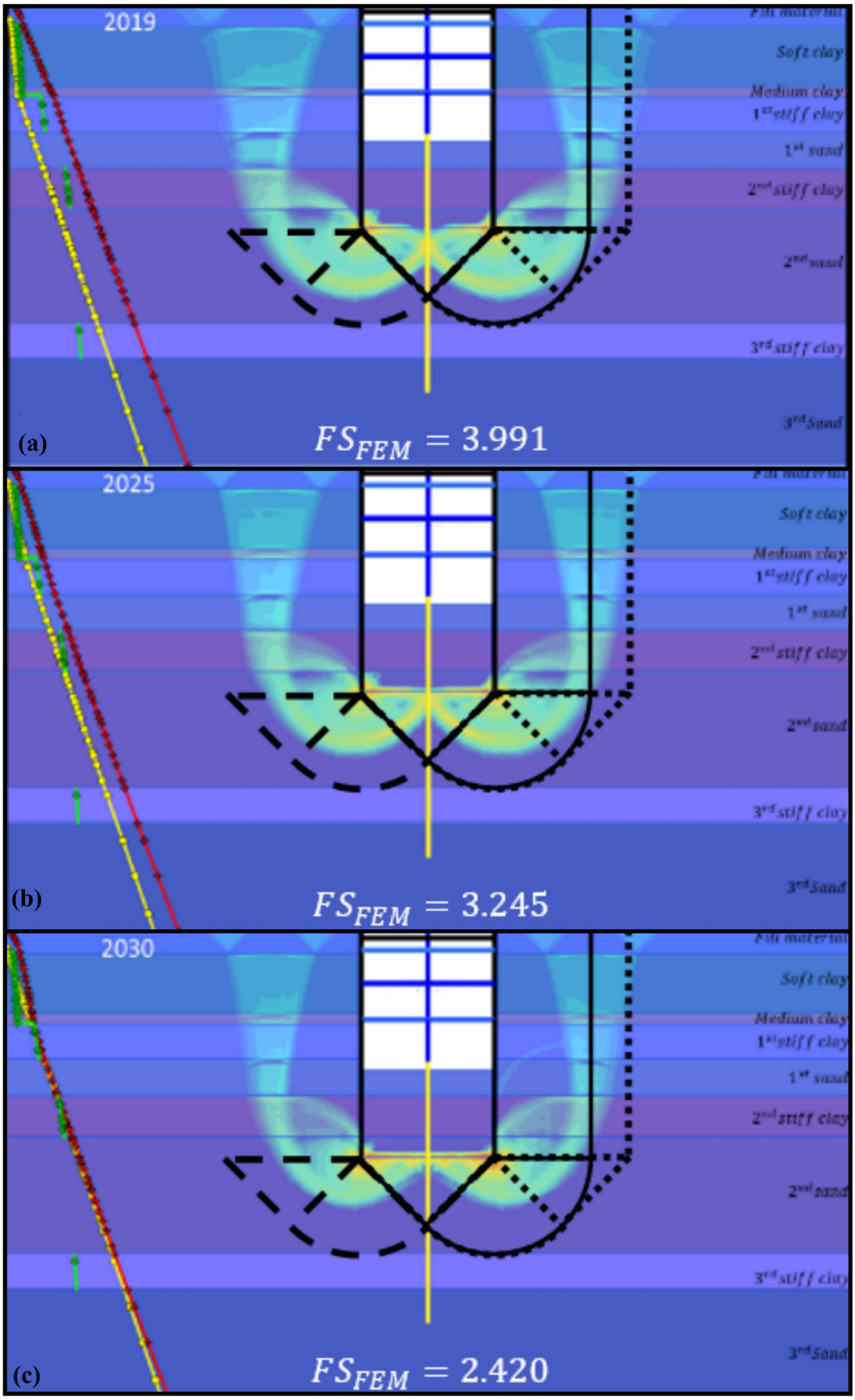

Figure 15. Failure mechanism at MRT Orange-Line Hua Mak Station with groundwater changes: (**a**) simulation year 1960, (**b**) simulation year 1997, and (**c**) simulation year 2030.

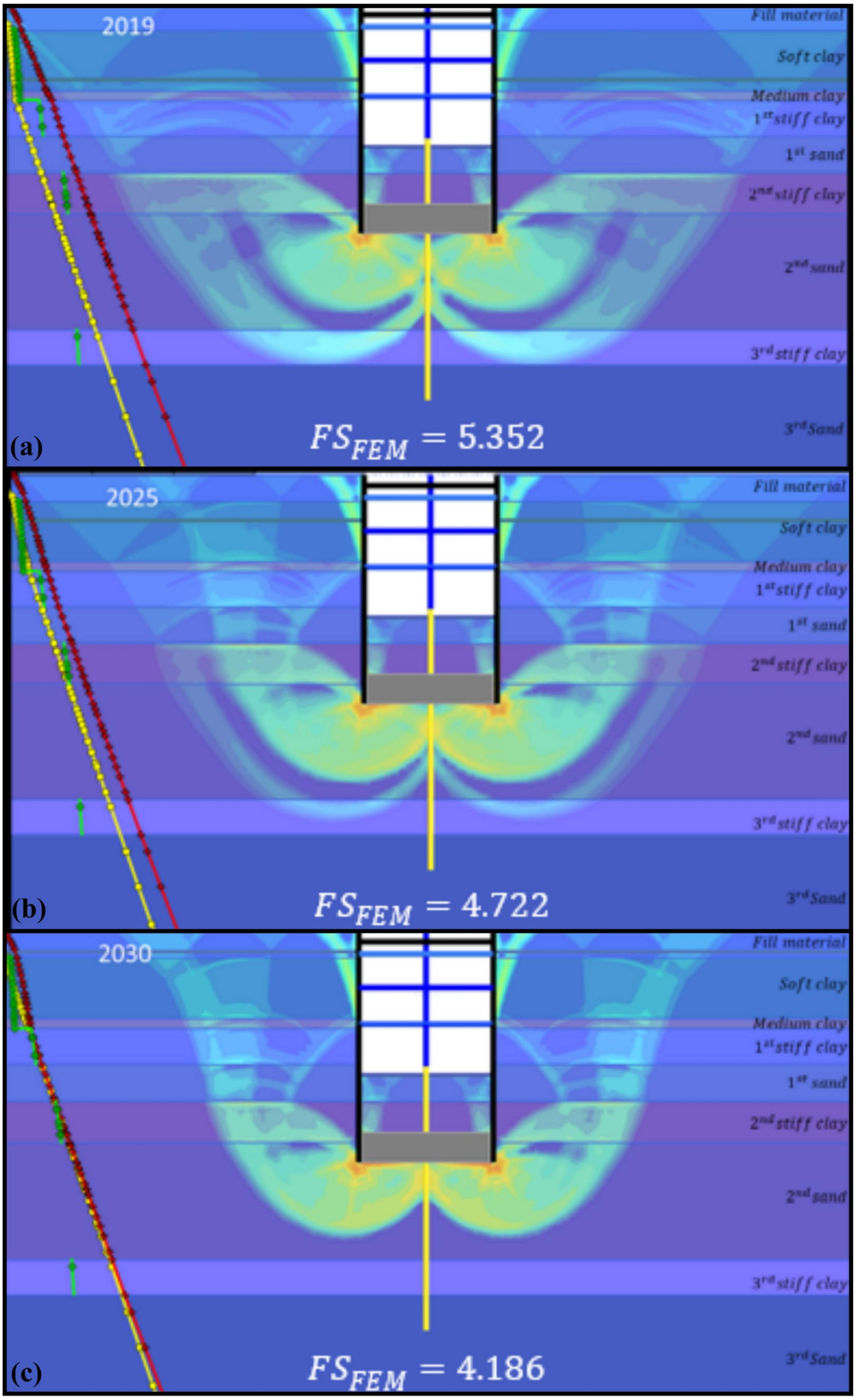

Figure 16. Failure mechanism at MRT Orange-Line Hua Mak Station using slab grouting with groundwater changes: (**a**) simulation year 1960, (**b**) simulation year 1997, and (**c**) simulation year in 2030.

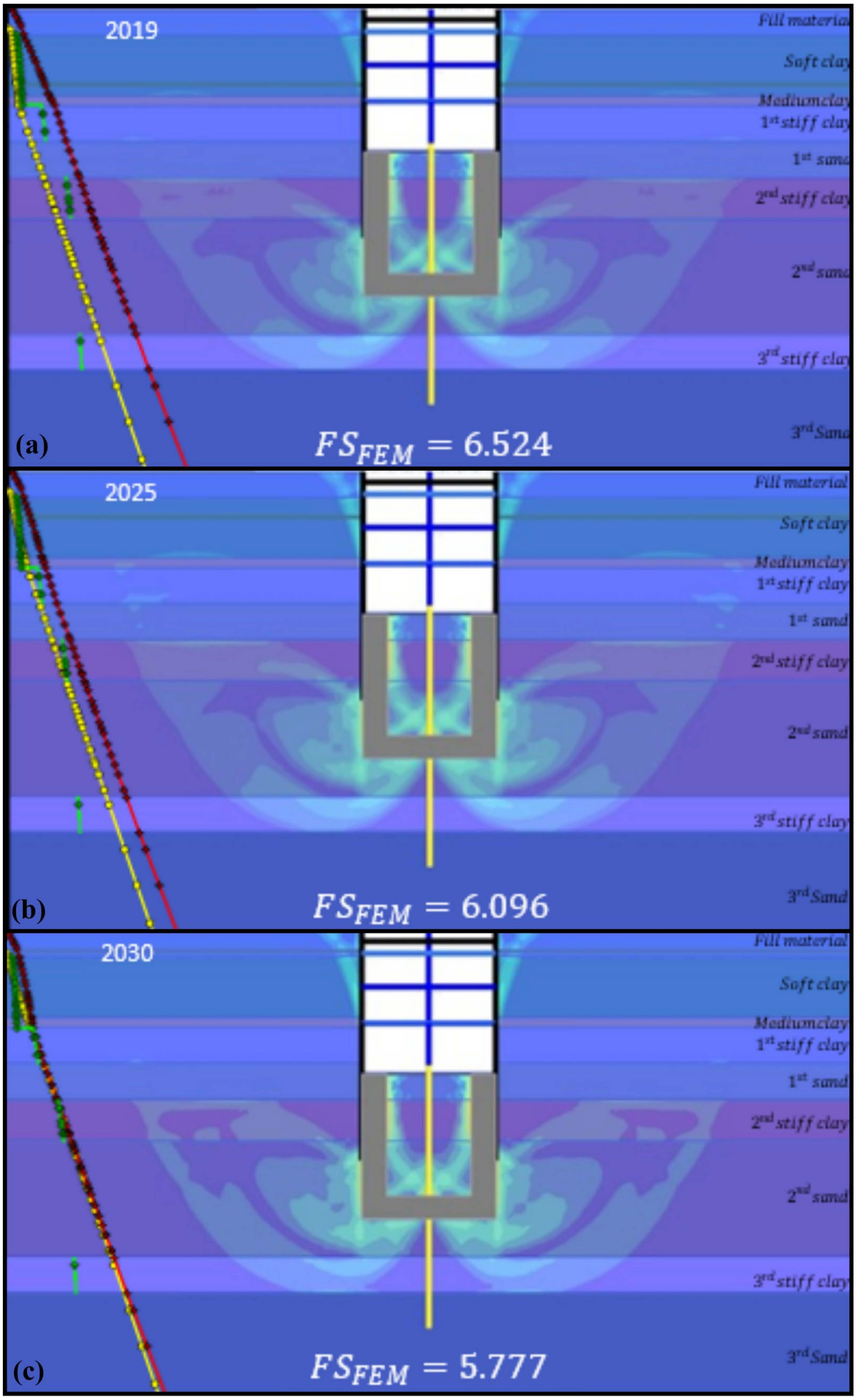

Figure 17. Failure mechanism at MRT Orange-Line Hua Mak Station using U-shape grouting with groundwater changes: (**a**) simulation year 1960, (**b**) simulation year 1997, and (**c**) simulation year 2030.

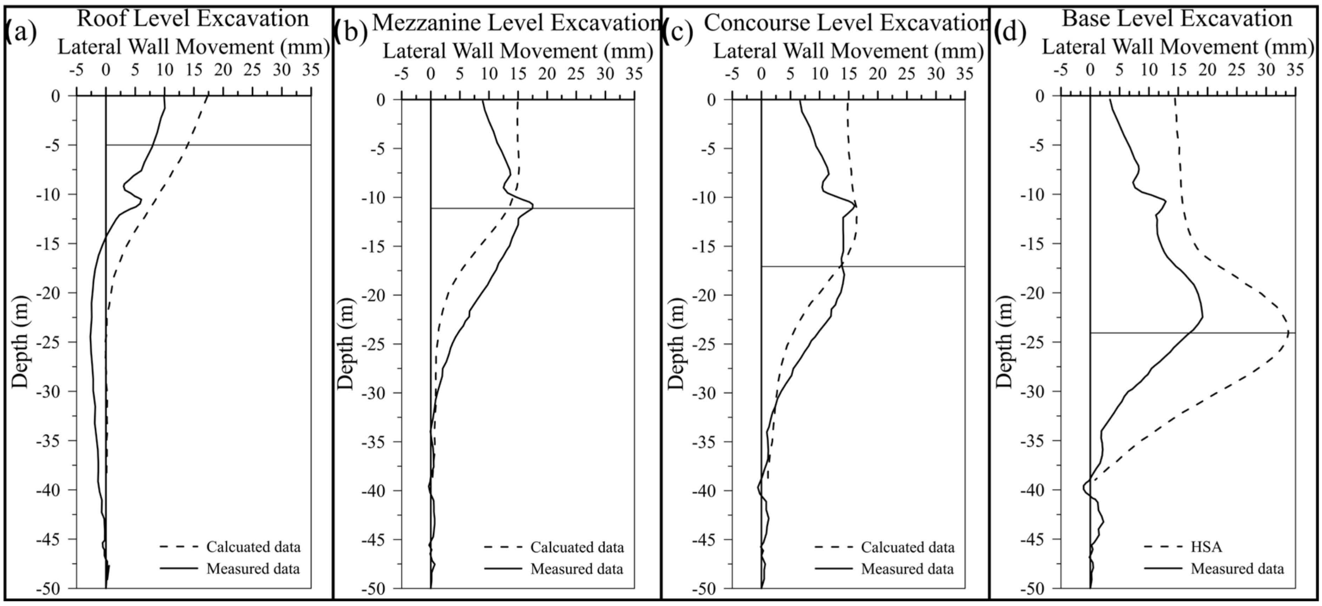

Figure 18. Comparison wall deflection at MRT Orange-Line Hua Mak Station between model-estimation and monitoring data.

5. Conclusions

This study provides a comprehensive analysis of basal heave stability in deep excavations within Bangkok's soft clay, particularly under the influence of confined groundwater recovery. The findings underscore the complexities associated with groundwater dynamics and their impact on excavation stability, contributing to the field of geotechnical engineering.

- Groundwater recovery significantly alters effective stress conditions, leading to increased risks of basal heave.
- Traditional analytical methods inadequately address the complexities of soil behavior in response to fluctuating groundwater levels.
- Numerical simulations indicate a substantial reduction in safety factors during groundwater recovery phases, highlighting the vulnerability of deeper excavations.
- This study identifies critical parameters, such as wall embedment depth and undrained shear strength, that influence stability outcomes.

The research outcome demonstrates the necessity for advanced numerical modeling techniques to enhance predictive accuracy for basal heave failures. This study contributes valuable insights into excavation design practices and establishes a framework for future research aimed at mitigating hydraulic heave risks. Despite these advancements, gaps remain in localized empirical guidelines for safety assessments in varying soil conditions. Further studies are indeed recommended to refine modeling approaches and develop tailored guidelines that consider the unique hydrogeological context of urban environments like Bangkok, ultimately improving the safety and integrity of excavation projects. In addition to these recommendations, a significant avenue for advancement lies in the expansion of current modeling techniques to incorporate three-dimensional (3D) analysis. The implementation of 3D modeling would allow for a more comprehensive representation of complex excavation geometries, soil–structure interactions, and spatial variations in soil properties and groundwater conditions. This approach could capture corner effects, non-uniform loading conditions, and asymmetrical excavation shapes that are often oversimplified in two-dimensional analyses. Moreover, 3D modeling could provide more accurate predictions of ground movements and stress distributions around the excavation, particularly in cases where the plane strain assumption may not be entirely valid. By integrating 3D modeling techniques with the refined approaches tailored to Bangkok's specific hydrogeological context, engineers and practitioners can develop more robust and accurate predictive tools. These advanced models would not only enhance the understanding of excavation behavior in challenging urban environments but also contribute to the development of more efficient, cost-effective, and safer excavation designs.

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