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Advanced Sheet Pile Curtain Design: Case Study of Cotonou East Corniche

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Abstract

This paper delves into the critical aspects of sheet pile walls in civil engineering, highlighting their versatility in soil protection, retention, and waterproofing, all while emphasizing sustainability and efficient construction practices. The paper explores two fundamental approaches to sheet pile design: limit equilibrium methods and numerical techniques, with a particular focus on finite element analysis. Utilizing the robust PLAXIS 2016 calculation code based on the finite element method and employing a simplified elastoplastic model (Mohr-Coulomb), this study meticulously models the interaction between sheet pile walls and surrounding soil. The research offers valuable insights into settlement and deformation patterns that adjacent buildings may experience during various construction phases. The central objective of this paper is to present the study's findings and recommend potential mitigation measures for settlement effects on nearby structures. By unraveling the intricate interplay between sheet pile wall construction and neighboring buildings, the paper equips engineers and practitioners to make informed decisions that ensure the safety and integrity of the built environment. In the context of the Cotonou East Corniche development, the study addresses the limitations of existing software, such as RIDO, in predicting settlements and deformations affecting nearby buildings due to the substantial load supported by sheet pile walls. This information gap necessitates a comprehensive study to assess potential impacts on adjacent structures and propose suitable mitigation measures. The research underscores the intricate dynamics between sheet pile wall construction and its influence on the local environment. It emphasizes the critical importance of proactive engineering and vigilant monitoring in managing and mitigating potential hazards to nearby buildings. To mitigate these risks, the paper recommends measures such as deep foundations, ground improvement techniques, and retrofitting. The findings presented in this study contribute significantly to the field of civil engineering and offer invaluable insights into the multifaceted dynamics of construction-induced settlement. The study underscores the importance of continuous evaluation and coordination between construction teams and building owners to effectively manage the impacts of sheet pile wall construction on adjacent structures.

Keywords

Sheet Pile Walls and Structural Analysis, Soil-Structure Interaction Modeling, Structural Sustainability, Cotonou East Corniche, Sustainable Construction, Plaxis Calculation Code, Settlement Mitigation

1. Introduction

Sheet pile walls are essential components in civil engineering, serving diverse purposes such as soil protection, retention, and waterproofing, especially in marine construction projects. Beyond their functional benefits, these structures contribute to sustainability through efficient material usage and environmentally friendly construction methods. Designing sheet pile walls involves intricate considerations of their interaction with the surrounding soil, falling under two broad categories: limit equilibrium methods and numerical techniques, including finite element and finite difference principles.

The acceleration and expansion of construction activities in densely populated urban areas typically lead to the creation of structures that often necessitate excavation supported by retaining walls. Due to spatial limitations, these excavations are situated adjacent to existing structures and buildings, with their stability posing a critical concern throughout various stages of the project.

Moreover, these excavation endeavors exert a notable impact on the stress conditions in the surrounding soil, and the modification of these stresses can induce movements that might result in significant disruptions to nearby structures. The precision of predicting these movements is presently inadequate due to the intricate nature of the problem [1].

In general, regulatory guidelines such as Eurocode 7 usually mandate the verification that the induced movements from a project remain within acceptable limits. To advance and refine calculation methods, it is imperative to simultaneously conduct both quantitative and qualitative observations on the behavior of retaining walls. These observations serve as a benchmark for numerical calculations and aid in enhancing both empirical and semi-empirical calculation methodologies.

The interest in understanding the impacts of excavations supported by bracing systems (strutting) has spurred numerous research endeavors (Balay J [2], Dysli M *et al.* [3], Potts and Fourie [4], Jardine *et al.* [5]) to examine the influence of various factors on soil movements and structural behavior.

Calculating retaining structures, irrespective of their type, frequently involves applying thrust and buttress actions to assess the loads imposed by the soil on the structure. The calculation methods, as outlined in documents like Eurocode 7-1 and Delattre [6], encompass empirical and semi-empirical, analytical, and numerical approaches.

Regarding empirical and semi-empirical methods, they are based on a framework that incorporates the observed behavior of structures. The pioneering works of Coulomb [7] and Boussinesq [8], subjected to numerous experimental validations, laid the foundation. After Rankine's [9] contributions, Boussinesq [8] proposed a triangular distribution of thrust stresses on a retaining wall for granular material, with stresses increasing linearly with depth. However, the evolution of transportation networks in the early twentieth century compelled engineers to construct underground metro lines, necessitating lateral excavation supported by strutted screens. Instrumentation of these structures enables the swift collection of measurements related to their behavior, revealing deviations from the triangular distribution law predicted by Rankine [9] or Boussinesq [8] (Delattre [6]). This discrepancy is attributed, on one hand, to a relative flexibility allowing deflection between supports and, on the other hand, to a screen kinematics where deflection tends to increase with depth.

In general, empirical and semi-empirical methods have seen significant development, particularly in Germany and the United States, drawing on a partly shared experimental foundation. In Germany, the prevalent method for designing retaining screens is of a semi-empirical nature (Sonja M [10]). Analytical calculations based on classical Coulomb and Rankine principles determine thrust, with redistribution contingent on the support type and conditions.

Concerning American research, the initial design proposal for retaining structures is credited to Terzaghi [11], who formulated a trapezoidal pressure redistribution diagram applicable to excavations in sands. Peck [12] proposed a similar diagram for excavations in plastic clays, based on measurements during the construction of the Chicago subway and assumptions by Terzaghi [13]. With new experimental data from diverse construction sites, these initial diagrams have been refined, allowing researchers (Terzaghi and Peck [14]; and Tschebotarioff in particular [15]) to present diagrams supported by extensive experimental validation.

This study addresses an information gap by utilizing the robust PLAXIS 2016 calculation code [16] based on the finite element method. Using a simplified elastoplastic model (Mohr-Coulomb), the interaction between soil and structure is meticulously modeled. Model parameters are established through rigorous standard tests, such as triaxial and pressuremeter tests. Simulation results offer valuable insights into settlement and deformation patterns neighboring buildings may undergo during various phases of sheet pile wall construction.

The central focus of this article is to present the findings of this study and suggest potential remedies to mitigate settlement effects on adjacent buildings. By unraveling the intricate interconnection between sheet pile wall construction and neighboring structures, engineers and practitioners can make well-informed decisions for the safety and integrity of the built environment.

In the context of the 2016-2021 government action program aimed at creating a favorable environment for tourism development and boosting the national and regional economy, projects like the "Route des pêches" (Fishing Route) and the development of the East Corniche of Cotonou were initiated. Tourism, being the second-largest foreign exchange earner after cotton, generated 93.4 billion FCFA in 2018 [17], contributing 5.2% to the country's GDP. It employed 201,300 people in 2018 and accounted for 6% of the active population in 2006 [18]. The East Corniche of Cotonou development involves stabilizing the embankment along the lagoon using various retaining structures, including sheet pile curtains.

Within this context, sheet pile walls play a crucial role, with the RIDO software being employed for modeling. However, RIDO's constraint lies in conducting localized analyses and lacking the capability to predict settlements and deformations affecting nearby buildings due to the substantial load supported by the sheet pile walls [19]. This information gap necessitates a comprehensive study to assess potential impacts on adjacent structures and propose suitable mitigation measures.

The ensuing sections of this article will delve deeper into the methodology used for modeling, present simulation results, and engage in a detailed discussion concerning practical implications and potential engineering solutions. This exploration will illuminate the multifaceted dynamics during each construction phase, focusing on discerning patterns of settlement and deformation.

2. Materials and Methods

2.1. Study Area Description

The structure is a sheet pile wall with a tie rod at the top and capped with a coping beam, designed to support a significant amount of backfill where a road will be constructed in the Cotonou channel. It is situated at a distance of 0.9 meters from the neighboring buildings. This channel, also known as the Cotonou Lagoon, serves as a link between Lake Nokoué and the Atlantic Ocean.

The tie rod is anchored to anchor piles placed 17 meters behind the main sheet piles. The specific area of focus in this study is point P5 (Pk 0 + 250), as referenced in the geotechnical survey report of the East Corniche of Cotonou. At this location, the buildings are near the structure, consisting of sheet pile walls, with a distance of about 3 meters between the anchor sheet pile and the lakeside hotel. Figure 1 gives the location of the corniche.

2.2. Defining Materials Properties

The different properties of various materials need to be defined based on their

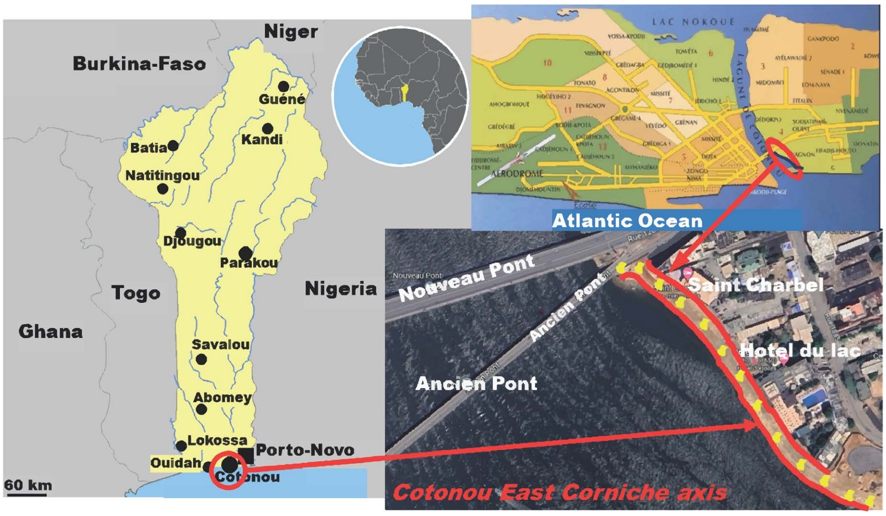

Figure 1. Cotonou east corniche project, location plan.

type (soil and interface, plate, anchor, geogrid, etc.), the behavior model, and the specific parameters that characterize them. For soils, besides defining their mechanical characteristics and interfaces with other types of elements, it is also necessary to specify the hydraulic behavior of the soil (drained, undrained, or non-porous).

2.2.1. Characteristics of the Materials to Be Utilized as Backfill Material

Table 1 provides specific material characteristics for two types of backfill materials: Granular Backfill and Common Backfill. These characteristics are crucial because they influence how these materials will behave under various loading conditions.

Key properties provided for each backfill type are [20]:

- Friction Angle (ϕ): This parameter represents the internal resistance of the material to shearing forces. A higher friction angle implies greater shear resistance and stability.
- Young's Modulus (E_m): This property indicates the stiffness of the material. Higher Young's modulus values suggest a stiffer material that deforms less under loading.
- Wet Unit Weight: This value reflects the density of the material when saturated with water. It is crucial for understanding the material's density and how it contributes to overall structural behavior.

The following values are considered for verification.

2.2.2. Layers Characteristics and Sheet Piles Specifications

Table 2 and Table 3 meticulously unravel the distinct attributes of various soil layers integrated into the model, alongside the precise specifications detailing the characteristics of the sheet piles. The integration of these intricate specifics assumes paramount importance as they faithfully mirror real-world scenarios within the simulation.

Table 1. Backfill Material Characteristics (Andrei, 2021) [21].

Properties	Granular Backfill	Common Backfill
Friction Angle (ϕ)	35˚	30˚
Young's Modulus (Em)	20 MPa	15 MPa
Wet Unit Weight	2.1 t/m^3	2.0 t/m^3

Table 2. Characteristics of the Layers in the Geometry.

ID	Name	Type	γ_{unsat}	γ_{sat}	k_x	k_y	ν	E_{ref}	C_{ref}	ϕ
			[KN/m^3]	[KN/m^3]	[m/day	[m/day]	[--]	[KN/m^2]	[KN/m^2]	[˚]
1	Common Fill	UnDrained	20.0	23.0	1.00	1.00	0.30	15000	0.00	30.00
2	Granular Fill	UnDrained	21.00	24.00	1.00	1.00	0.30	20000	0.00	35.00
3	Sand	UnDrained	18.00	20.00	1.00	1.00	0.30	5000	0.00	25.00
4	Clayey Sand	UnDrained	16.00	18.00	1.00	1.00	0.30	11100	10.00	10.00
5	Silty	Non-porous	20.00	20.00	0.00	0.00	0.30	20000	0.00	30.00
6	Concrete	Non-porous	25.00	25.00	0.00	0.00	0.30	13000	1.00	31.00

Table 3. Sheet piles specifications.

ID	Name	Type	EA	EI	W	ν	M_p	N_p
			[KN/m]	[KN·m^2/m]	[KN/m^2]	[--]	[KN·m/m]	[KN/m]
1	AZ18-700	Elastic	2.923E^6	7.938E^6	1.1	0.00	1E^{15}	1E^{15}
2	AZ28-700N	Elastic	4.2E^6	1.34E^5	1.5	0.00	1E^{15}	1E^{15}

For each distinct soil stratum, the information provided in **Table 2** encompasses an array of parameters carefully chosen to encapsulate the nuances of its mechanical response:

The model accommodates a spectrum of six soil layers, spanning from Common Fill, Granular Fill, Sand, Clayey Sand, Silty soil, to Concrete. The particulars expounded in **Table 2** distinctly specify whether these layers are characterized as UnDrained or Non-porous, thereby shedding light on their behavior concerning water flow dynamics.

Critical parameters such as γ_{unsat} and γ_{sat} take center stage as unsaturated and saturated unit weights, playing a pivotal role in influencing the soil's density and its corresponding reaction to external loading forces.

Further insights are gleaned from the permeabilities in both the x and y directions, represented as k_x and k_y, intricately shaping the pathways through which water traverses within the intricate fabric of the soil.

The Poisson's ratio, symbolized as ν, offers valuable understanding into the material's deformation characteristics when subjected to diverse loading orientations.

The Reference Young's Modulus, noted as E_{ref}, forms a foundational element contributing to the material's stiffness and its overall response under varying conditions.

Of equal importance is the Reference Cohesion, denoted as C_{ref}, shedding light on the material's shear strength in its reference state.

Lastly, the friction angle, represented as ϕ, brings to a close the series of parameters, essentially underlining the material's intrinsic resistance against shear-induced forces.

The meticulous articulation of these properties collectively establishes the behavioral framework for the soil layers, intricately dictating their interactions and engagements with other constituents within the model.

The tables provided in this study, namely **Table 2** and **Table 3**, serve as pivotal repositories of comprehensive insights into the distinctive attributes of the soil layers and the specifications that govern the behavior of the sheet piles when subjected to loading. These details are of paramount importance in ensuring the fidelity of the simulation's representation of real-world conditions.

Delving into the specifics, **Table 2** meticulously presents an array of parameters that intricately capture the mechanical response of each soil layer. The six diverse soil layers, ranging from Common Fill, Granular Fill, Sand, Clayey Sand, Silty, to Concrete, are detailed in terms of their drained or non-porous behavior, thereby outlining their interaction with water flow. The parameters enumerated include:

γ_{unsat} and γ_{sat}: These unsaturated and saturated unit weights significantly influence the soil's density and its reaction to applied loads. k_x and k_y: The permeabilities in the x and y directions play a pivotal role in dictating the soil's hydraulic behavior. ν: Poisson's ratio assumes importance in understanding the material's deformation response when subjected to varying loading directions. E_{ref}: The reference Young's Modulus provides crucial insights into the material's stiffness characteristics. C_{ref}: The reference cohesion parameter offers a glimpse into the material's shear strength under reference conditions. ϕ: The friction angle parameter signifies the material's inclination to resist shear forces. Collectively, these parameters intricately define the mechanical response of each soil layer, orchestrating their behavior and interactions with other elements in the simulation.

Turning our attention to **Table 3**, it meticulously delineates the mechanical attributes that define the behavior of the sheet piles, specifically the AZ18-700 and AZ28-700N elastic type sheet piles (**Figure 2**), under varying loading conditions. The parameters expounded include [22] [23].

EA: Axial stiffness, illuminating the sheet pile's aptitude to withstand axial loads. EI: Flexural stiffness, crucial in portraying the sheet pile's resilience against bending moments. W: Unit weight, shedding light on the sheet pile's weight per unit length. ν: Poisson's ratio, unveiling the material's deformation behavior. M_p: Bending moment capacity, a defining attribute in its response to bending forces. N_p: Axial force capacity, outlining the sheet pile's resistance to

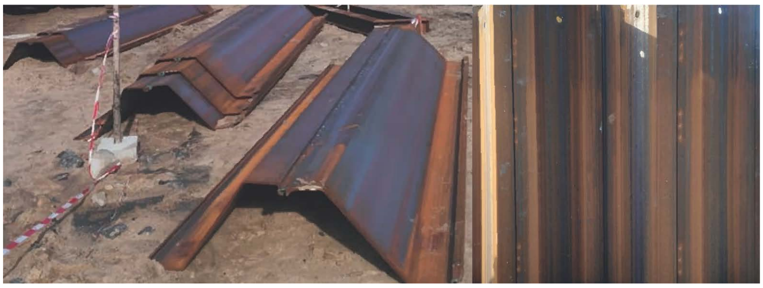

Figure 2. Sheet piles employed for the project.

axial forces.

In unison, these parameters intricately mold the dynamics of interaction between the soil layers and the sheet piles when subjected to external loads. Their harmonious interplay delineates the responses of these elements to external forces and each other. These attributes collectively contribute to an accurate representation of the sheet piles' behavior under external loads and their intricate interactions with the surrounding soil.

2.2.3. Water Level

This section provides information about the water levels and hydrological conditions that will affect the analysis. Different lake levels based on varying conditions and return periods are listed, as well as tidal levels for high and low tides. These water levels are crucial for understanding how water pressures and hydrostatic forces will impact the stability of the structure and adjacent buildings.

The lake levels as provided in the APD report are indicated in **Table 4**.

Figure 3 presents the initial water pressure model employed in the soil modeling process.

Based on experience from a neighboring project (rehabilitation works of the south quay of the port of Cotonou, located 2 km from our project) and as a conservative approach, the present work adopted the following tidal levels:

- High tide: +0.47 m IGN.
- Low tide: −0.13 m IGN.

According to the results of the boreholes, the existing soil mainly consists of sand to a depth of at least 6 m below the surface at the location of the sheet piles. Based on the in-situ test results, the following assumptions are considered:

- Internal friction angle in the TN layer: $\phi' = 25^\circ$.
- Cohesion: $c' = 0$.
- Passive pressure: $\sigma = -2/3 \cdot \phi'$.
- Active pressure: $\sigma = 0$.

A superficial stratum having a depth of 1 - 2 meters, depending on the cross-sections, is neglected as it is primarily composed of loose sand with pockets of silt in some areas. Therefore, the passive pressure can be neglected over a depth of approximately 2 meters.

The information provided here about the peak and trough of the tide levels

Table 4. Lake levels [21].

Hydrological Condition	Lake Level (m, from IGN)
During low water	0.64
Average level	0.70
Flood having a recurrence interval of T = 2 years	1.08
Flood with having a recurrence interval of T = 10 years	1.25
Flood with having a recurrence interval of T = 100 years	1.36

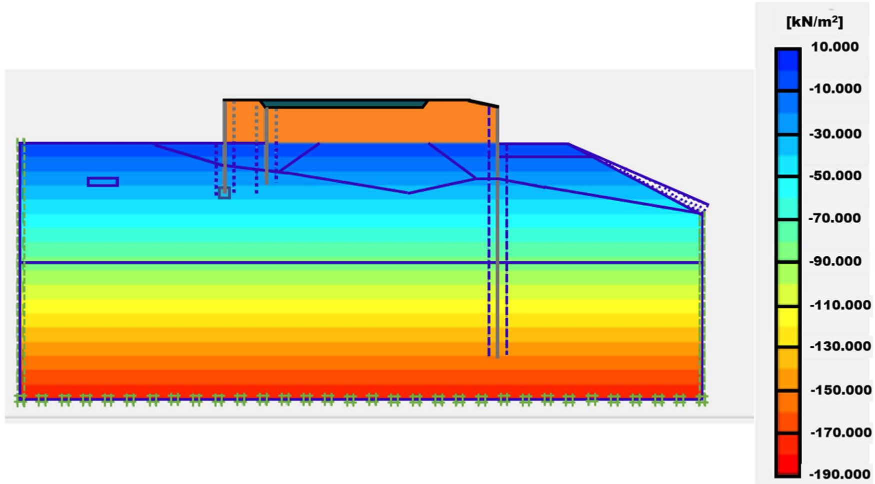

Figure 3. Water pressure.

are important boundary conditions for the model.

2.3. Modeling Procedure

In this subsection, the study will present the key steps involved in a calculation using the PLAXIS 2016 software.

2.3.1. Geometry

The initial step in PLAXIS involves defining the geometry, which includes several available properties:

- Geometrical lines: Utilized to depict various soil layers. These lines define the various layers and components in the model. They serve as the foundation for creating a physical representation of the project.
- Plate command: Employed to specify slender structures with tensile, compressive, and flexural strength. This tool is primarily used for modeling walls, beams, shells, plates, and rigid zones, especially elements with significant extension perpendicular to the modeling plane [21]. Plate command commands are used to define structural elements with specific mechanical properties. They represent walls, beams, shells, plates, and other structural components that interact with the soil.
- Anchors (fixed head, node-to-node): Elastic elements utilized to model con-

nections from a single point or between two points. These are elastic elements used to model connections between points or structures. They allow to simulate the behavior of anchors, which can influence the stability of the system.

- These elements collectively create the physical representation of the analyzing systemas illustrated in **Figure 4**.

2.3.2. Boundary Conditions

Once the geometry is defined, the boundary conditions need to be set, which involve specifying the prescribed displacements and stresses on the outer limits of the model. If no boundary condition is assigned to a section, the software assumes by default that the element is not subjected to any external force and is free to move in all directions. A variety of limits conditions can be imposed, including those that prescribe a displacement in a specific direction or apply a force in a given direction. PLAXIS 2016 provides several tools to create a comprehensive range of boundary conditions, such as distributed force, point force, fixed support, sliding support, etc. [24]. These conditions dictate how the model interacts with external forces and constraints. These conditions are essential for understanding how external forces and constraints affect the behavior of the model.

2.3.3. Mesh Generation

The mesh defines the discretization of the geometry into smaller elements, allowing for numerical analysis. Mesh generation involves specifying mesh density and refining specific regions of interest. In this paper mesh generation is performed automatically, which is a notable feature of PLAXIS 2016 (**Figure 5**). The operator can change the mesh refinement using different options (very coarse, coarse, medium, fine, very fine). Furthermore, the user holds the flexibility to refine specific regions of the soil and the vicinity of certain elements using the "refine" options available in the mesh menu. After completing the meshing process,

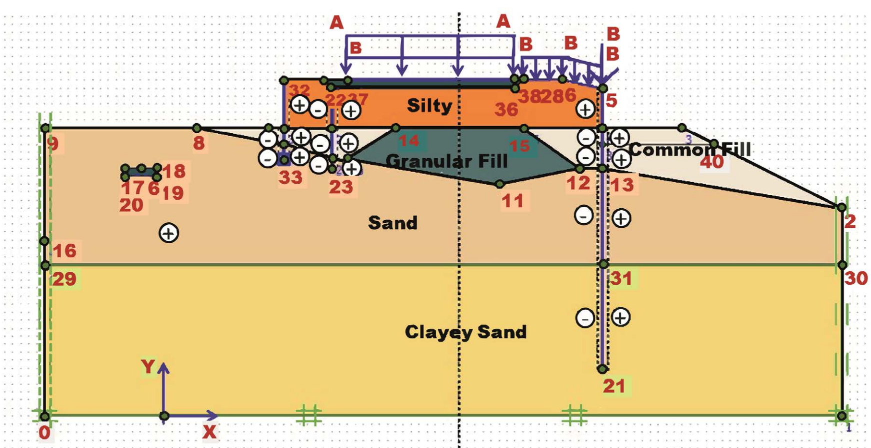

Figure 4. Modeling Geometry at Pk 0 + 250.

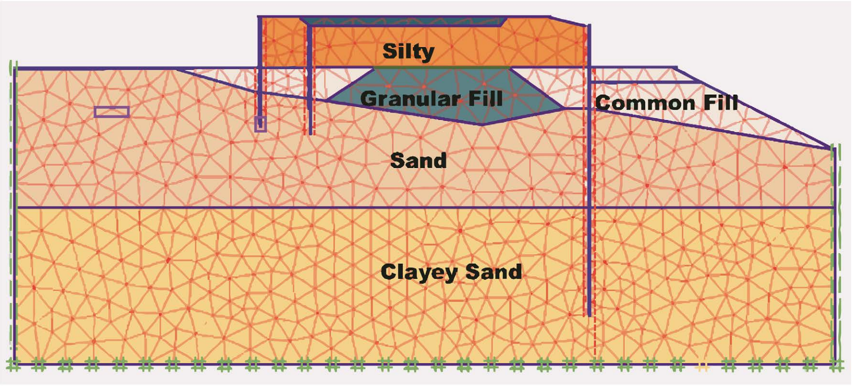

Figure 5. Extremely fine mesh.

it is crucial to set the initial soil conditions, which typically involves defining the coefficient of earth pressure at rest.

2.3.4. Initial Conditions

The definition of initial conditions involves two distinct steps. Initially, when the window for initial conditions opens, only the soil is activated. The operator activates the structural elements (displacements, imposed stresses, anchors, plates) that correspond to the initial time step and deactivates the soil elements that are not relevant to this initial time step. A switch button provides access to two different windows, each representing the model's geometry: the first one, named "initial pore pressure," allows defining the initial groundwater level and generating corresponding interstitial pressures; the second window allows generating initial stresses within the massif. To Summarize, initial condition involves activating or deactivating elements and defining initial groundwater levels, interstitial pressures, and initial stresses.

- Activation and Deactivation: specific elements can be activated or deactivated, both soil and structural, to represent the initial state of the system.
- Initial Groundwater Levels: Defining initial groundwater levels is crucial for capturing the initial water pressures within the soil.
- Interstitial Pressures and Initial Stresses: These factors influence the initial state of stress within the system.

2.3.5. Calculation Phases

After completing all these parameter settings, the calculations can be initiated by clicking the "Calculation" button [25] [26]. The PLAXIS input interface will then close, making way for a new calculation interface. Phase 0, representing the initial state of the structure, is already calculated. This interface allows defining the phasing of the construction modeling, and new calculation phases can be created. For each phase, modifications to the geometry can be made through the same interface used for defining initial conditions. Elements can be activated or deactivated to make changes. Adjustments to the groundwater level and certain properties of materials and elements other than soil can be made. The intensity level and position of limit conditions for displacements and stresses can also be modified. Once the phasing of the study is completed, characteristic points can be placed for calculating PLAXIS result curves. After pressing "Calculate," the calculations are initiated, and once completed, the results can be viewed using the "Output" button. PLAXIS enables two types of consolidation calculations:

- Staged construction: This tool allows visualizing the soil after allowing it to consolidate for a specified time interval set by the user.
- Minimum pore pressure: This tool determines the time and state of the soil after allowing it to consolidate for a sufficiently long time until the pore pressure is consistently below the value set by the user.
- Phased Approach: Calculation phases allow to simulate the project's construction and evolution over time. Each phase represents a different state or scenario.
- Modifications: Within each phase, properties, boundary conditions, and elements can be modified to match the evolving conditions.
- Staged Construction and Consolidation: staged construction and consolidation processes can be simulated, which mirror real-world scenarios.

2.3.6. Staging of the Construction

1. Phase 0: Initial State

The geometry of the initial state is depicted in Figure 6.

2. Phase 1: Work Zone Preparation

Backfilling of the core with granular fill material up to the elevation of approximately +0.90 m. The material utilized should have a friction angle of 35˚ and be placed with slopes of approximately 2V/3H. It is imperial note that this material does not support the installation of sheet piles. Thus, precautions should be taken to prevent any interference with the alignment of the future sheet pile curtains. Figure 7 illustrates the geometry of the Work Zone Preparation.

3. Phase 2: Construction of the Common Fill Work Platform (See Figure 8)

The material for the working platform must have a minimum friction angle of 30˚ and a low percentage of fines to reduce the risk of secondary settlement and its susceptibility to water. Additionally, after the backfill is placed, it should have a minimum Young's modulus of E = 20 MPa to prevent sand rearrangement

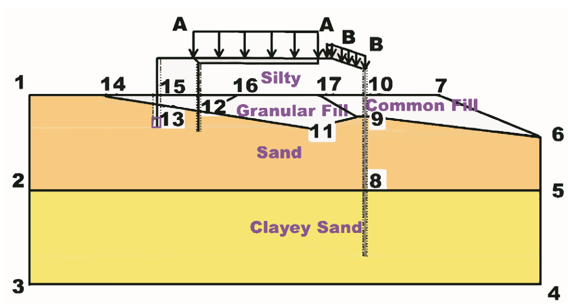

Figure 6. Initial phase geometry.

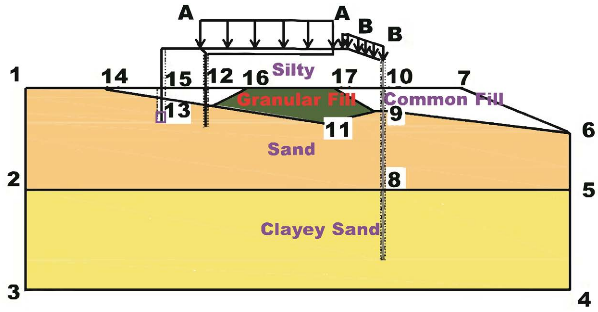

Figure 7. Work area preparation.

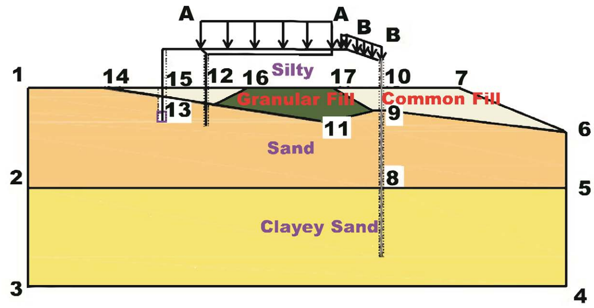

Figure 8. Construction of the common fill work platform.

settlements. If this condition is not met, a vibrocompaction campaign may be required.

4. Phase 3: Installation of Front and Rear Sheet Pile Walls, Walers, and Anchor Tie Rods

The tie rods should be slightly tensioned using turnbuckles to compensate for the installation clearances and thus prevent significant movements of the sheet piles during the additional backfilling phase. Figure 9 illustrates the geometry of Installation of Walers and Tiebacks in Common Embankment.

5. Phase 4: Backfilling up to the Underside of the upper Beam and Construction of the Road (See Figure 10)

The material used for the platform should have a minimum friction angle of 30˚ and a low percentage of fines to reduce the risk of secondary settlement and its sensitivity to water. Additionally, the backfill, once placed, should have a minimum Young's modulus of $E = 20$ Mpa to prevent sand rearrangement settlements.

6. Phase 5: Road Commissioning (See Figure 11 for the Geometry)

3. Results and Discussion

3.1. Results Visualization

Result Visualization includes:

- Mesh deformation
- Displacements (vertical, horizontal, total) and deformations

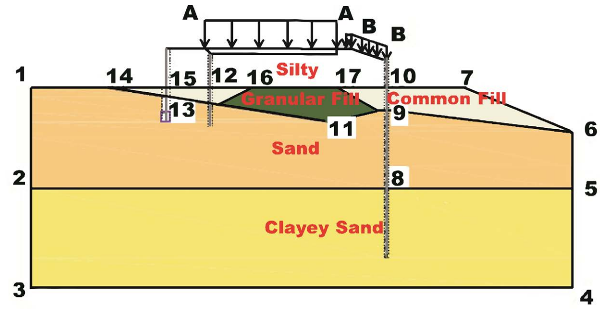

Figure 9. Installation of walers and tiebacks in common embankment.

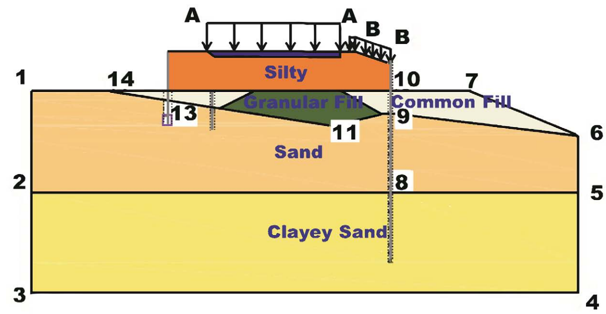

Figure 10. Backfilling up to the underside of the upper beam and road construction.

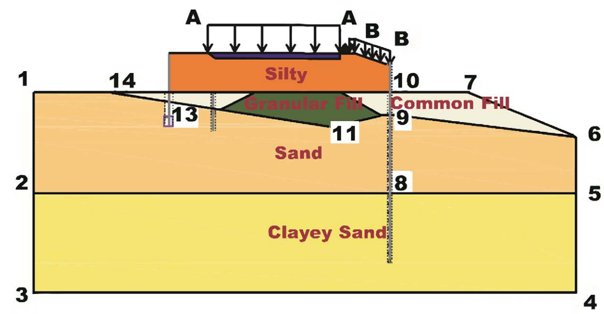

Figure 11. Road Commissioning.

- Velocities and accelerations (applicable during dynamic analysis)
- Total stresses and effective stresses
- Over-consolidation coefficient, reduction factor, and plastic deformation points
- Saturation degree, flow pattern, and water level
- Incremental deformations and stresses resulting from various phases in comparison to the initial state

1. Phase 1: Work Zone Preparation

The maximum vertical displacement measures is 52.79×10^{-3} m, and occurs below the granular fill (See Figure 12).

The displacement diagram for cross-section AA, taken on the side of the buildings, illustrates that the maximum vertical displacement is -3.99×10^{-3} m (See Figure 12). The granular backfill is introduced, but it doesn't support sheet pile installation. No significant immediate concern for building foundations. The displacement values for cross-section AA are detailed in Table 5.

2. Phase 2: Construction of the Common Fill Work Platform

The Maximal vertical displacement is 71.26×10^{-3} m (See Figure 13). The displacement diagram for cross-section AA, taken on the side of the buildings, shows that the maximum vertical displacement is -15.95×10^{-3} m (See Figure 13, Maximum displacement beneath the platform). Material used for the platform is introduced, causing vertical displacements in the soil. Some settlement is observed but doesn't pose immediate risks to the buildings. The displacement values for cross-section AA are provided in Table 6.

3. Phase 3: Installation of Front and Rear Sheet Pile Walls, Walers, and Anchor Tie Rods

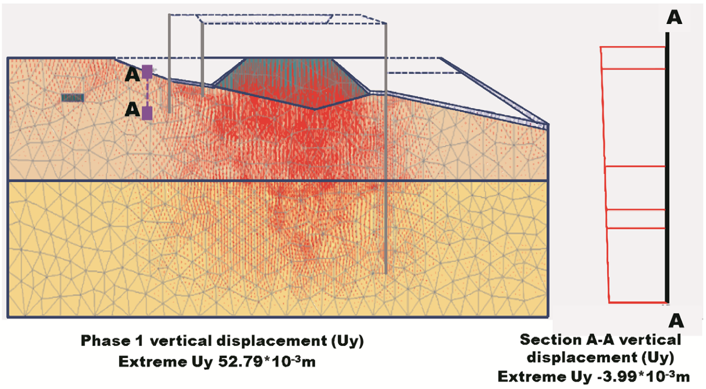

Figure 12. Phase 1 vertical displacement.

Table 5. Section A-A vertical displacement at Phase 1.

X [m]	Y [m]	Uy [10^{-3} m]
5.476	17.389	0.090
5.476	17.017	−3.993
5.476	17.017	−3.993
5.476	16.815	−3.930
5.476	16.815	−3.930
5.476	15.874	−3.728
5.476	15.874	−3.728
5.476	15.452	−3.672
5.476	15.452	−3.672
5.476	15.288	−3.646
5.476	15.288	−3.646
5.476	14.577	−3.525

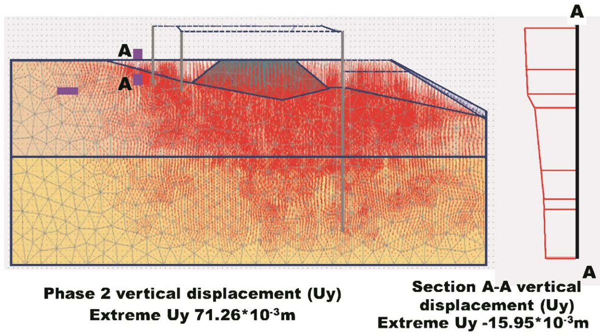

Figure 13. Phase 2 vertical displacement.

Table 6. Section A-A Vertical Displacement at Phase 2.

X [m]	Y [m]	Uy [10^{-3} m]
5.476	18.00	−15.953
5.476	17.389	−15.703
5.476	17.389	−15.703
5.476	17.017	−15.501
5.476	17.017	−15.501
5.476	16.815	−12.889
5.476	16.815	−12.889
5.476	15.874	−10.957
5.476	15.874	−10.957
5.476	15.452	−10.179
5.476	15.452	−10.179
5.476	15.288	−10.024
5.476	15.288	−10.024
5.476	14.577	−9.519

The Maximal vertical displacement is 71.37×10^{-3} m (See **Figure 14**). Maximum displacement beneath the sheet pile wall is -16.33×10^{-3} m (See **Figure 14**). Installation of sheet piles, walers, and tie rods introduces vertical displacements in the soil. It's essential to tension tie rods to prevent significant sheet pile movements during backfilling. The displacement values for cross-section AA are provided in **Table 7**.

In the third phase of the analysis, the sheet pile experiences a maximum vertical displacement of 55.88×10^{-3} m (See **Figure 15**), localized at the uppermost part of the sheet pile. This value remains well below the threshold of 0.1m, falling within the acceptable range for such displacements.

Furthermore, the most significant bending moment is recorded at 6.5 m from the sheet pile's upper end, with a value of 801.69×10^{-3} KN·m/m. In terms of shear forces, the highest magnitude of 980.47×10^{-3} kN/m occurs at a distance of

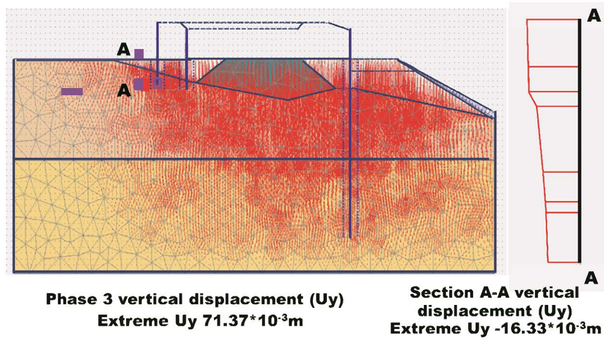

Figure 14. Phase 3 vertical displacement.

Table 7. Section A-A vertical displacement at Phase 3.

X [m]	Y [m]	Uy [10^{-3} m]
5.476	18.00	−16.328
5.476	17.389	−16.057
5.476	17.389	−16.057
5.476	17.017	−15.856
5.476	17.017	−15.856
5.476	16.815	−13.242
5.476	16.815	−13.242
5.476	15.874	−11.302
5.476	15.874	−11.302
5.476	15.452	−10.517
5.476	15.452	−10.517
5.476	15.288	−10.360
5.476	15.288	−10.360
5.476	14.577	−9.859

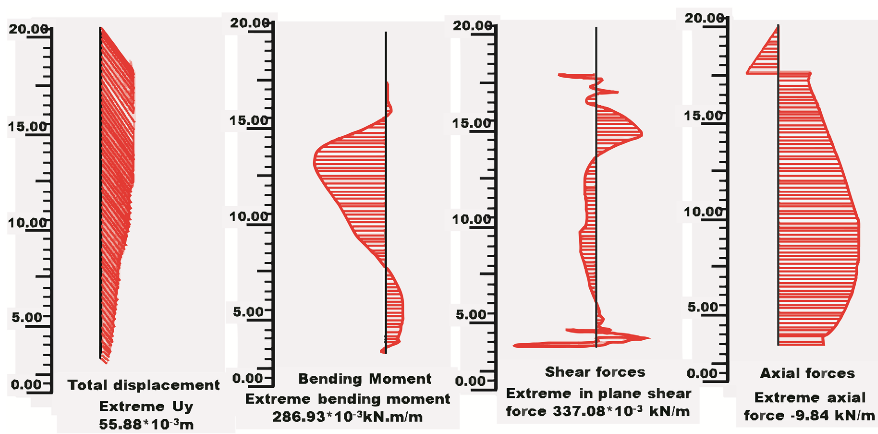

Figure 15. Loading conditions on the main sheet pile in Phase 3.

17 m from the top of the sheet pile. The normal force, on the other hand, reaches a value of −9.65 kN/m at a position 8m from the sheet pile's upper end.

4. Phase 4: Backfilling up to the Underside of the upper Beam and Construction of the Road

The vertical displacement attains its peak magnitude at 205.93 × 10^{-3} m, while concurrently, the most extensive downward shift materializes below the backfill, registering −25.93 × 10^{-3} m as shown in **Figure 16**. Notably, the backfill process culminating at the capping beam stage and subsequent road construction incites a consequential vertical displacement trend within the soil. Evident is a noteworthy settlement, a phenomenon with the potential to impact neighboring structures. Comprehensive insight into these displacement values, particularly concerning cross-section AA, is conveniently laid out in **Table 8**:

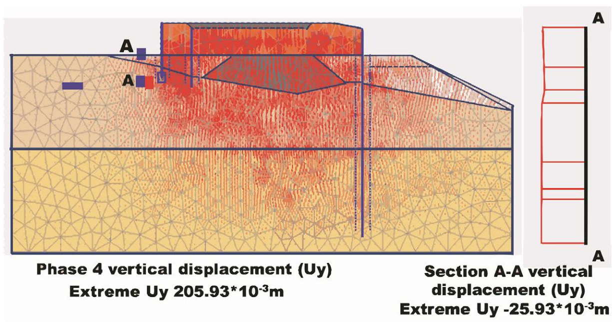

Figure 16. Phase 4 vertical displacement.

Table 8. Section A-A vertical displacement at Phase 4.

X [m]	Y [m]	Uy [10^{-3} m]
5.476	18.00	−25.321
5.476	17.389	−23.903
5.476	17.389	−23.903
5.476	17.017	−23.815
5.476	17.017	−23.815
5.476	16.815	−25.249
5.476	16.815	−25.249
5.476	15.874	−25.928
5.476	15.874	−25.928
5.476	15.452	−25.626
5.476	15.452	−25.626
5.476	15.288	−25.614
5.476	15.288	−25.614
5.476	14.577	−25.833

In Phase 4, the paramount total vertical displacement of the sheet pile materializes right at its apex, amounting to 79.90 × 10^{-3} m, a magnitude comfortably below the 0.1 m threshold that is considered within the realm of acceptability (See Figure 17). Concurrently, the pinnacle bending moment registers at 95.45 × 10^{-3} KN·m/m, positioned 8 meters away from the sheet pile's summit. In a similar vein, the maximum shear force attains 43.94 × 10^{-3} kN/m, a manifestation at a 4.5-meter distance from the sheet pile's upper extremity (See Figure 17). Simultaneously, the normal force asserts itself at −115.61 kN/m, positioned 11 meters away from the uppermost part of the sheet pile.

5. Phase 5. Road Commissioning

The utmost vertical displacement quantifies to 246.19 × 10^{-3} m. Correspondingly, the greatest displacement beneath the roadway substratum manifests as −19.17 × 10^{-3} m, as depicted in the displacement profile of cross-section AA, recorded on the side aligned with the structures (See Figure 18).

Moreover, the ongoing augmentation of road infrastructure perpetuates vertical displacement, fueling the potential for protracted subsidence that could impinge upon the soundness of building foundations. These displacement attributes are meticulously outlined in Table 9.

In Phase 5, the culmination of the total vertical displacement atop the primary sheet pile attains a pinnacle magnitude of 86.04 × 10^{-3} m, notably below the 0.1

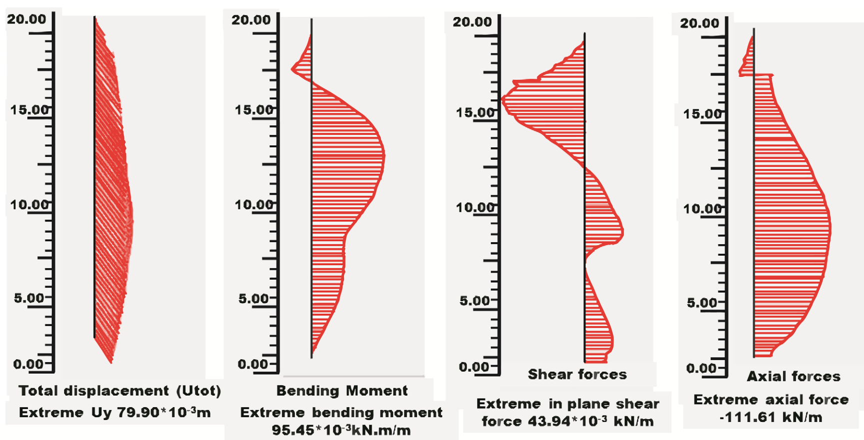

Figure 17. Loading conditions on the main sheet pile in Phase 4.

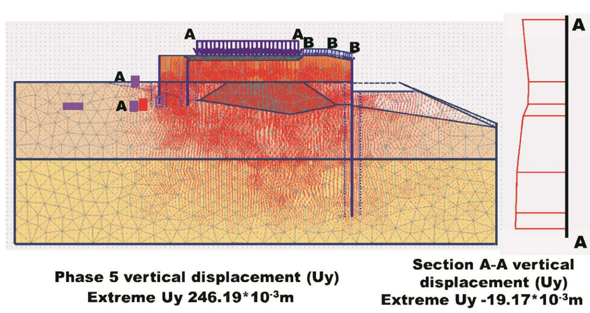

Figure 18. Phase 5 vertical displacement.

Table 9. Section A-A vertical displacement at Phase 5.

X [m]	Y [m]	Uy [10^{-3} m]
5.536	18.00	−16.123
5.536	17.311	−14.368
5.536	17.311	−14.368
5.536	17.000	−14.363
5.536	17.000	−14.363
5.536	16.831	−16.358
5.536	16.831	−16.358
5.536	16.043	−18.657
5.536	16.043	−18.657
5.536	15.478	−18.968
5.536	15.478	−18.968
5.536	15.258	−19.174

m threshold. Concomitantly, the preeminent bending moment reaches 152.97×10^{-3} KN·m/m, strategically positioned 7.5 meters from the sheet pile's leading edge (See Figure 19). Correspondingly, the paramount shear force registers at 80.40×10^{-3} kN/m, a feat occurring at a distance of 3.5 m from the sheet pile's commencement. Furthermore, the normative force amounts to −75.48 kN/m, its manifestation transpiring 9.6 meters away from the sheet pile's outset.

Figures 20-23 depict the process of sheet pile installation at the construction site.

3.2. Discussion

The erection process of the sheet pile curtain structure encompasses several distinct phases, each contributing to a range of displacements and settlements within the encompassing soil. These consequential soil adjustments possess the capacity to impart effects upon neighboring structures. Let us proceed to dissect and elucidate the ramifications of the sheet pile curtain structure on the proximate buildings:

- The maximum total displacement in the structure is 246.19×10^{-3} m.
- Settlement is observed beneath the structure, both on the lagoon side and building side.
- The tie rod undergoes slight inclination due to sheet pile movements.

Initial Phases (Phases 0-2):

- These stages encompass the establishment and assembly of the working platform, as well as the sheet pile wall installation.
- While there is some settlement attributable to material introduction, the degree of displacement remains relatively moderate.

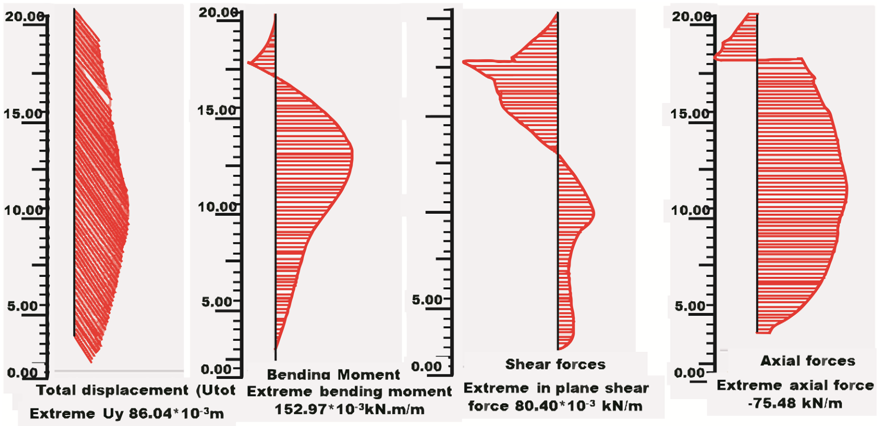

Figure 19. Loading conditions on the main sheet pile in Phase 5.

Figure 20. Installation of sheet piles on construction site.

Figure 21. Installation of sheet piles on construction site.

Figure 22. Installation of sheet piles completed on site.

Figure 23. Installation of sheet piles completed on site.

- The initial phases are less prone to generating substantial disruptions in proximity to neighboring structures. The displacements witnessed during these stages are comparably minor and improbable to exert noteworthy impacts on the nearby buildings.

Phase 3: Installation of Sheet Pile Walls and Tie Rods:

- The implementation of sheet pile walls and tie rods can induce vertical soil displacements. Tensioned tie rods play a role in mitigating excessive sheet pile movement during backfilling.
- There is a possibility of slight settlement in neighboring buildings due to the vertical displacements resulting from the installation of sheet piles. Although measures are in place to minimize these movements, some degree of settlement near adjacent structures is plausible.
- The presence of tie rods aids in managing lateral sheet pile movements, thereby restraining their impact on the surrounding structures.
- On the whole, the effects on buildings are anticipated to be controllable, and the construction sequence incorporates measures to regulate these movements.

Phase 4: Backfilling and Road Construction:

- This phase entails extensive backfilling to the level of the capping beam and the construction of a road. The process results in noteworthy settlement as a consequence of both the backfilling up to the capping beam and the road construction.
- The amplified load and vertical displacement stemming from the backfilling

can give rise to differential settlement in neighboring structures. The considerable vertical displacement has the potential to induce differential settlement among proximate buildings.

- Structures in closer proximity to the sheet pile curtain may encounter more pronounced settlement compared to those positioned farther away due to their immediate association with the loaded zone.

Phase 5: Road Commissioning:

- The concluding phase maintains the trend of inducing settlement as a result of further road construction.
- Structures located in the surrounding area could encounter additional settlement, with greater emphasis on those closest to the construction site. This could potentially have implications for their structural stability.

3.2.1. Line of Influence and Differential Settlement

Consider the following scenario:

- Foundation 1: A foundation located at a depth of 2 m and 3 m away from the retaining wall.
- Foundation 2: A foundation located at a depth of 2 m and 8 m away from the retaining wall.

Differential settlement between Foundation 1 and Foundation 2 is shown in Table 10. The settlement evolution at these foundations during the different phases of construction is as follows:

- Foundation 1, located nearer to the retaining wall, exhibits distinct settlement behavior compared to Foundation 2.
- The degree of differential settlement escalates as construction progresses, with the most notable contrast occurring during Phase 4.
- Varied settlement patterns among adjacent structures can result in uneven stress and strain distribution.
- Differential settlement bears the potential to trigger structural degradation, fracture development, and misalignment issues.

Figure 24 shows Settlement Variation of Soil under Foundation 1 and Foundation 2.

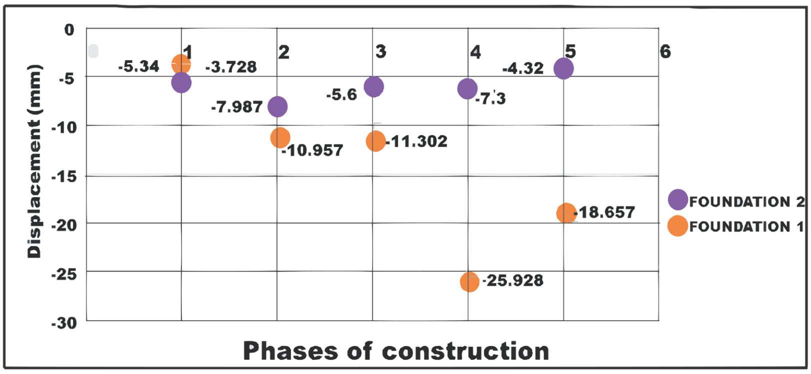

Figure 24. Settlement variation of soil under Foundation 1 and Foundation 2.

Table 10. Differential settlement between Foundation 1 and Foundation 2.

Phases	Differential Settlement (mm)
1	1.612
2	−2.97
3	−5.702
4	−18.628
5	−14.337

3.2.2. Analysis and Interpretation

- The construction phases induce significant settlement in the soil beneath the adjacent buildings;
- The differential settlement between Foundation 1 and Foundation 2 indicates uneven ground movement;
- Building foundations should be designed to accommodate these settlements without structural distress;
- The accumulated settlement should be compared to building tolerances and code limits;
- Structural monitoring during and after construction is crucial to ensure building safety.

3.2.3. Mitigation and Recommendations

- The variation in settlement among adjacent buildings' foundations can induce uneven stress distribution within the structures.
- Designing foundations to withstand projected settlements while upholding structural integrity is essential.
- To counter potential adverse effects, deep foundations or ground improvement techniques might be necessary. Isolating foundations from potential settlement using techniques like elastomeric bearings can protect structures.
- Structural robustness is imperative to endure the projected ground movements in buildings. Depending on soil conditions, techniques like vibrocompaction might be employed to reduce settlement potential.
- The adoption of appropriate design, reinforcement, and construction methodologies is crucial to curbing potential structural harm.
- The accumulation of settlement should undergo assessment against stipulated building tolerance thresholds and local building codes.
- Should settlements approach or surpass these thresholds, corrective actions may be essential (Buildings possess a defined tolerance for settlement).
- To ensure occupant safety, cumulative settlement must remain within acceptable parameters.
- Vigilant and continuous monitoring of building responses during and post-construction is pivotal.
- If concerns arise from settlements, retrofitting or reinforcement strategies might be required to assure safety.

- Consider retrofitting or reinforcement if settlements approach critical limits;
- Transparent communication with building occupants and stakeholders is pivotal for expectation management.
- Informing them about construction stages, probable impacts, and mitigation strategies can allay apprehensions.

In summation, the influence of the sheet pile curtain structure on adjacent buildings is a complex interplay of construction phases, soil characteristics, and building design. The most critical phase for potential impacts is the backfilling and road construction stage. In-depth analysis, monitoring, and coordination among engineers, constructors, and building owners are necessary to ensure that the adjacent buildings remain structurally sound and safe during and after the construction process.

4. Conclusions

In this extensive examination of "Innovative Techniques Unveiled in Advanced Sheet Pile Curtain Design", the study delved into the complexities of geotechnical engineering, focusing on soil-structure interaction (SSI). The investigation centered on sheet pile design, highlighting two primary methodological categories: Limit Equilibrium Methods (LEM) and Soil-Structure Interaction Methods (SSIM).

LEM methods, rooted in classical principles and analytical simplicity, serve as valuable tools for preliminary design considerations. However, their limitations become apparent in addressing the intricate complexities of real-world soil-structure interaction. Conversely, SSIM methods, exemplified by the SSI-SR approach, offer precision and depth. Leveraging numerical techniques such as Finite Element (FE) and Finite Difference (FD) analyses, these methods empower engineers to navigate the multifaceted dynamics of soil-structure interaction.

The exploration extended into the realm of SSI-FE, uncovering its significant role in civil engineering. By integrating Finite Element analysis with considerations for soil-structure interaction, the SSI-FE method provides engineers with a holistic understanding of structural interaction with the dynamic geotechnical environment.

In the pursuit of precision, the article systematically examined critical components governing SSIM methods, including reaction laws (RL), P-Y relationships, and elastic stiffness (K_{ss}). These insights furnish engineers with the necessary tools to navigate the complex geotechnical design landscape.

Significantly, the study acknowledged the importance of the Mohr-Coulomb constitutive model while candidly recognizing its limitations. This balanced perspective guides practitioners in making informed decisions during geotechnical analyses, emphasizing the consideration of advanced models in complex scenarios.

As this paper concludes its exploration, the future of geotechnical engineering is recognized as one of continuous learning and innovation. Armed with advancing technology and a deepening understanding of soil-structure interaction, the scientific community moves forward, prepared to address the evolving challenges of the engineering landscape. The commitment remains focused on ensuring the safety, stability, and efficiency of geotechnical structures through cutting-edge design and analysis techniques.

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Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest Statement

On behalf of all authors, the corresponding author states that there is no competing interests regarding the publication of this research.

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