JACEP

Journal of Applied Civil Engineering and Practices

Online (e-ISSN): e-ISSN 3109-2551 || 2025, Volume 1, No. 2, Pp. 108-125

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To cite this article:

Nugroho J, Elviana. (2025). The Evaluation of Soldier Pile Reinforcement for the Church Building Wall Due to Ramp Foundation Excavation Works. *Journal of Applied Civil Engineering and Practice*, 1 (2), Pp. 108-125. doi: 10.21831/jacep.v1i2.2104

To link to this article:

http://doi.org/10.21831/jacep.v1i2.2104

Journal of Applied Civil Engineering and Practice by the Department of Bachelor of Applied Science in Civil Engineering, Faculty of Vocational, Universitas Negeri Yogyakarta.

2025, Volume 1, No. 2, Pp. 108-125, e-ISSN 3109-2551

Journal of Applied Civil Engineering and Practice

JACEP

Journal homepage: https://journal.uny.ac.id/publications/jacep/index

Research paper

The Evaluation of Soldier Pile Reinforcement for the Church Building Wall Due to Ramp Foundation Excavation Works

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ARTICLE INFO

Article History:
Received: September 24, 2025
Accepted: January 8, 2026
Published: January 10, 2026

Keywords:
Soldier Pile, PLAXIS 2D, Safety Factor, Deformation, Displacement

How To Cite:
Nugroho J, Elviana. (2025). The Evaluation of Soldier Pile Reinforcement for the Church Building Wall Due to Ramp Foundation Excavation Works. *Journal of Applied Civil Engineering and Practice*, 1 (2), Pp. 108-125. doi: 10.21831/jacep.v1i2.2104

ABSTRACT

Purpose: The construction of the Jakarta Gelora Marriott Hotel encountered technical challenges during the excavation of the ramp foundation, which was located in proximity to an existing church building. This site constraint posed potential risks to the stability of the church foundation, thereby necessitating the implementation of a reinforcement method. The purpose of this study is to evaluate the performance of soldier piles as retaining walls in resisting lateral earth pressures induced by excavation, with emphasis on safety factor, deformation, and lateral displacement.

Methods/Design: The research was conducted using a quantitative approach through numerical modelling with the PLAXIS software. The input data included soil investigation results, soldier pile geometric parameters, and the uniform load of the church structure obtained from ETABS modelling. The analysis was carried out in reference to SNI 8460:2017, SNI 1726:2019, SNI 2847:2019, and SNI 1727:2020. The soil profile consisted of medium-to-high plasticity silty clay at depths of 0–9 m, and low-plasticity sandy silt at depths of 9–27 m.

Findings: The findings indicated that the soldier pile was subjected to significant internal forces during excavation. A short-term (plastic) analysis was performed for an excavation depth of 3 m. The maximum deformation obtained from the second excavation stage was 56.59 mm, while the total lateral displacement reached 58.19 mm. These values exceeded the allowable deflection limit of 40 mm.

Practical implication: Conversely, the safety factors for the first and second excavation stages were 4.2 and 3.2, respectively. These results demonstrate that the soldier pile system satisfied the safety requirements, as the minimum acceptable safety factor is 2.

INTRODUCTION

Containing The development of infrastructure in major Indonesian cities, particularly Jakarta, continues to grow rapidly in line with the increasing demand for business and tourism facilities. The construction of the Jakarta Gelora Marriott Hotel represents one of the strategic development projects located in an industrial area of Central Jakarta. The project is a five-star hotel situated on Jl. Palmerah Timur, West Jakarta, developed by PT. SSP Sejahtera Property was constructed by PT Total Bangun Persada Tbk. The foundation system adopted for this project is a deep foundation using bored piles. The number of bored piles employed is relatively large, given that the development involves a high-rise building that requires a robust structural foundation.

The bored piles in this project are located within the basement area, which consists of four floors. The construction of the ramp foundation, providing vehicle access from the ground floor to the basement level one, presented significant challenges due to the limited available space. The ramp area was situated adjacent to the wall of an existing church building. This situation raised serious concerns regarding the potential for damage to the church foundation during the excavation process, particularly because the position and characteristics of the existing foundation were not fully known. Thus, the selection of an appropriate retaining wall reinforcement method became critical. This study focuses on analyzing the stability of soldier piles as earth-retaining structures. The primary objective is to assess the displacement of soldier piles caused by lateral soil pressure following installation, thereby ensuring the safety of the church foundation throughout the construction process (Lafit et al., 2021).

Structural safety was considered the foremost priority, as the existing church building represented a critical structure that must be preserved. Therefore, any reinforcement method selected was required to prevent structural damage to the existing building. This necessitated careful planning to optimize the limited working space. Additionally, the reinforcement method had to account for efficiency in terms of both construction time and cost, without compromising structural quality and safety. The chosen method also needed to minimize disturbances to activities surrounding the project site, particularly religious services at the church and other community activities in the area (Siregar, 2019).

Excavation near existing structures can trigger several mechanisms of damage, including lateral soil movement, ground settlement, structural cracking, and building tilting. Such risks are particularly critical for embedded wall and excavation projects in urban areas, where deformation control becomes a key requirement to protect nearby structures. In this case, the excavation adjacent to the existing church was underlain by soft clay. This soil type is highly susceptible to lateral movement and subsidence upon excavation, potentially leading to outward wall deflection and ground collapse behind the wall. As a result, the church foundation was at risk of cracking or tilting (Hardiyatmo, 2010).

Several methods are commonly used to support excavation walls in urban areas, including diaphragm walls, secant piles, sheet piles, and soldier piles. Diaphragm walls provide high stiffness and are effective in minimizing groundwater seepage; however, their construction requires substantial working space and higher costs (Bowles, 1996). Secant piles are also effective, particularly in conditions with high groundwater levels, but their drilling process is more complex and requires high precision. In contrast, soldier piles are relatively simple, rapid, and economical, making them widely used for shallow to medium-depth excavations, especially where working space is restricted (Grim Tech, 2023). Considering the project's proximity to the church building and the limited working area, this research emphasizes the application of reinforced concrete soldier piles as the most appropriate, safe, and efficient reinforcement method.

This study is expected to provide significant contributions to the advancement of knowledge in civil engineering, particularly in structural reinforcement. Based on the outlined problems, an in-depth investigation of soldier pile reinforcement that is safe, efficient, and effective is required. The study will analyse various factors influencing the performance of soldier pile retaining walls and evaluate their effectiveness in addressing the challenges faced in the Jakarta Gelora Marriott Hotel project.

METHODS/DESIGN

The research employed a quantitative approach, focusing on the processing of numerical data and concrete parameters. The study was carried out through direct observation of the project under investigation. Data collection began with obtaining soil investigation results from the structural consultant, PT Daya Creasi Mitrayasa, which conducted the geotechnical investigation in September 2022. In addition to the field soil data, discussions were also held with the Site Engineer of PT Total Bangun Persada Tbk, the main contractor, to review the reinforcement work required to prevent potential structural failures in the adjacent existing church building.

The soil data and structural weight of the existing church were processed by inputting the geometric parameters into the PLAXIS 2D software, supplemented by manual calculations to determine the Safety Factor (SF) of the reinforcement. The calculations referred to SNI 8460:2017 on Geotechnical Design Requirements, specifically Article 7.4 concerning retaining wall design provisions and Article 7.5 concerning soldier pile walls. Soldier pile reinforcement was modeled and analyzed to assess its effectiveness in resisting soil displacement by evaluating the resulting safety factor values.

This case study was based on the construction of the Jakarta Gelora Marriott Hotel, located approximately 200 meters from Palmerah Station, precisely at Jalan Gelora V No. 99 C, RT.2/RW.1, Gelora, Tanah Abang District, Central Jakarta, Special Capital Region of Jakarta.

Data Collection

Primary Data

Primary data consisted of measurements of the existing church building. These included direct field measurements to obtain the total structural weight, which was subsequently analyzed using ETABS V22. The results were then applied as uniform loads in PLAXIS to simulate the performance of the soldier pile. The primary data included building information, structural material properties, and element dimensions.

Secondary Data

Secondary data were obtained from the soil investigation report and laboratory testing of samples taken at various depths. The laboratory tests provided soil parameters such as cohesion, internal friction angle, dry unit weight, porosity, and void ratio. For PLAXIS analysis, the required parameters included soil elastic modulus, Poisson's ratio, cohesion, friction angle, dilatancy angle, saturated unit weight, and unsaturated unit weight.

Tools and Materials

The following tools and materials were utilized in this study:

- N-SPT soil investigation data
- Field measurement data of the existing church building
- ETABS V22 software for structural analysis of the church building
- PLAXIS 2D software for soldier pile reinforcement analysis
- Microsoft Excel for load calculations and input parameter preparation for soldier pile analysis

Data Analysis Method

The analysis was conducted by first calculating the total load of the existing church building to determine the equivalent uniform load, followed by numerical simulation using PLAXIS 2D. The calculations were carried out in reference to SNI 8460:2017, particularly Article 7.4 regarding retaining wall design and Article 7.5 regarding soldier pile retaining walls. PLAXIS 2D is a geotechnical engineering software used to model soil deformation and displacement. The software applies finite element analysis by discretizing the object into smaller elements, each interconnected through nodal points, so that the overall behavior of the system can be represented mathematically.

The reinforcement modelling adjacent to the church building was simulated using soldier piles in PLAXIS 2D to evaluate deformation, displacement, and safety factor values.

Existing Building Data

Table 1. Existing Building Information

No.	Description	Value	Unit
1	Building Function	Church	
2	Building Height	10	m
3	Typical Story Height	3	m
4	Roof Story Height	4	m
5	Number of Stories	3	–
6	Location	West Jakarta	
7	Structural System	SMRF (Special Moment Resisting Frame)	
8	Material	Reinforced concrete	

Material Definition

- Concrete: K-300 (f'c = 25 MPa)
- Main reinforcement steel: fy' = 320 MPa, diameter 16 mm
- Stirrup reinforcement steel: fy' = 280 MPa, diameter 10 mm

Structural Profiles Used in the Existing Church

- Reinforced concrete columns: K1-35×35, K2-20×20
- Reinforced concrete beams: B1-20/25, B2-15/20

Structural Modelling Procedure

The three-story church building was modelled using ETABS V22 based on manual measurements and relevant design codes. The modelling aimed to obtain the internal force distribution and structural performance of the church. The final output, the total structural weight, was required for defining the uniform load in PLAXIS 2D. The main modelling steps included:

1. Define Grid – Establishing reference lines to position elements such as beams, columns, and slabs.
2. Define Material – Assigning concrete and steel reinforcement material properties.
3. Define Structural Profiles – Assigning dimensions and materials for beams, columns, slabs, shear walls, and staircases.
4. Structural Modelling – Digital representation of the building in ETABS.
5. Connection Modelling – Using end length offsets and rigid zone factors to represent joint stiffness.
6. Slab Meshing – Auto-mesh options for slabs modelled as shell elements; diaphragms assumed rigid.
7. Support Conditions – Building supports were modelled as fixed supports.
8. Effective Seismic Weight Definition – Defined using mass source based on 100% dead load and superimposed dead loads (SIDL).
9. Response Spectrum Definition – Assigning earthquake loads via response spectrum functions.
10. Load Definition and Assignment – Assigning dead, live, and SIDL loads into load cases.
11. Structural Analysis – Running the model to obtain structural responses.
12. Required Output – Extracting total building weight through Modal Participating Mass Ratio (MPMR), multiplied by the building footprint area to determine uniform load input for PLAXIS 2D.

PLAXIS 2D Modelling

The soldier pile reinforcement adjacent to the church building was modelled in PLAXIS 2D to represent the maximum loading condition during ramp excavation.

Key modelling steps included:

- Geometry defined based on detailed engineering design (DED) of the project.
- Soil stratification obtained from field and laboratory investigations.
- Total building load applied as uniform pressure.

The input parameters consisted of soil properties, soldier pile characteristics, and the uniform load of the church building, all of which were assigned to the respective elements created in the model. The soil input parameters included:

Table 2. Soil Parameter Definitions

Parameter	Symbol
Elastic Modulus	E
Poisson’s Ratio	v
Cohesion	c
Internal Friction Angle	ϕ
Dilatancy Angle	ψ
Saturated Unit Weight	γ sat
Unsaturated Unit Weight	γ_unsat

- The geometry of the soil layers, soldier pile, and uniform building load was then modelled accordingly. Meshing was performed to discretize the model into finite elements, preparing it for numerical calculation. The mesh density could be defined as very coarse, coarse, medium, fine, or very fine, which directly influenced the accuracy of the results.
- The *Flow Conditions* were applied to define the groundwater table elevation at specific soil depths. If variations in groundwater levels were present, they could be incorporated at this stage.
- Finally, staged construction was simulated to represent actual site conditions. In this study, excavation was modelled to a depth of 3 meters. The staged construction phase served as the final step to obtain the required outputs, namely deformation, lateral displacement, and safety factor values.

RESULTS AND DISCUSSION

Soil Laboratory Testing Data

The soil laboratory testing for the Jakarta Gelora Marriott Hotel construction project was carried out by PT Daya Creasi Mitrayasa in September 2022. The primary objective of the geotechnical investigation was to obtain general information regarding the subsurface stratigraphy and soil profile at the project site. The investigation also aimed to identify the appropriate type of foundation to support the superstructure, based on allowable bearing capacity, permissible settlement, economic feasibility, and the anticipation of potential construction-related problems.

The investigation involved drilling, sampling, Standard Penetration Tests (SPT), Cone Penetration Tests (CPT), and a series of laboratory tests. Laboratory testing included index properties such as water content, specific gravity, and Atterberg limits.

In total, seven soil layers were identified at the Jakarta Gelora Marriott Hotel project site. However, since the soldier pile retaining wall employed in this study was designed to a depth of 7 meters, only two soil layers were required as input for the PLAXIS 2D model. The first layer extended from the ground surface to an elevation of –9.0 m and was classified as silty clay of medium-to-high plasticity (CH) (Source: Jakarta Gelora Marriott Soil Investigation Report, 2022).

This layer exhibited a medium-stiff consistency, indicating a soil condition with moderate stiffness—stronger than soft clay but not yet reaching a high stiffness level. The measured Standard Penetration Test (N-SPT) value for this layer was 5. Laboratory testing on samples from the surface to –9.0 m yielded the results presented in the following table.

Table 3. Soil Parameters of Layer 1

Parameter	Value	Unit
Water Content	53.65	%
Specific Gravity	2.67	–
Liquid Limit	70.27	%
Plastic Limit	32.34	%
Plasticity Index	37.93	%
Triaxial UU Test		
1. Cohesion	0.60	kg/cm^2
2. Friction Angle	5.1	°
Triaxial CU Test		
1. Cohesion	29	kN/m^2
2. Friction Angle	28.0	°
Consolidation Coefficient	1.20×10^{-3}	cm^2/s

The second soil layer, between elevations -9.0 m and -27.0 m, was classified as sandy silt with low plasticity (ML) and minor clay content. This layer was further divided into two sub-layers due to differences in consistency. The first sub-layer, from -9.0 m to -12.0 m, had an N-SPT design value of 20, while the second sub-layer, from -12.0 m to -27.0 m, had an N-SPT value of 54. Laboratory test results for this layer are presented below (Source: Jakarta Gelora Marriott Soil Investigation Report, 2022).

Table 4. Soil Parameters of Layer 2

Parameter	Value (–9.0 m to –12.0 m)	Value (–12.0 m to –27.0 m)
Water Content	51.21	52.12
Specific Gravity	2.66	2.66
Liquid Limit	67.41	65.35
Plastic Limit	32.59	34.07
Plasticity Index	34.82	31.28
Triaxial UU Test		
1. Cohesion	0.58	–
2. Friction Angle	6.2	–
Triaxial CU Test		
1. Cohesion	–	0.29
2. Friction Angle	–	32.2
Consolidation Coefficient	1.00×10^{-3}	–

Data Analysis

The stability of the retaining structure was analyzed using PLAXIS 2D. The primary objective of the PLAXIS modelling was to determine the bending moments and shear forces acting on the soldier pile. Before analyzing the retaining wall, the total load of the surrounding structures—

specifically the existing church building—was calculated with the aid of ETABS software. The structural load analysis was an essential preliminary step to obtain the total building load, which was then described as follows:

1. **Dead Load**

   The dead load calculation was carried out automatically by ETABS to avoid duplication; no additional manual input of dead load was required.

2. **Superimposed Dead Load (SIDL)**

   The superimposed dead loads of the church building consisted of two categories: area loads and line loads. The calculation of superimposed dead loads for the church building is presented in the following tables (Badan Standardisasi Nasional, 2019a, 2019b, 2020; Daulay, 2022).

Table 5. Superimposed Dead Loads (SIDL) on Floor Slabs

No.	SIDL on Floor Slabs	Load (kN/m^2)
1	Ceramic (19 mm) and mortar (25 mm)	1.10
2	Ceiling and hangers (10 mm gypsum)	0.18
3	Mechanical and electrical systems	0.19
4	Plumbing (clean and wastewater pipes)	0.20
	Total	**1.67**

Table 6. Superimposed Dead Loads (SIDL) on Roof Slabs

No.	SIDL on Roof Slabs	Load (kN/m^2)
1	Ceiling and hangers (10 mm gypsum)	0.18
2	Mechanical and electrical systems	0.19
3	Plumbing (clean and wastewater pipes)	0.20
4	Waterproofing layer	0.05
	Total	**0.62**

Table 7. Superimposed Dead Loads (SIDL) as Line Loads on Floor Slabs

No.	SIDL Line Loads on Floor Slabs	Load (kN/m^2)	Height (m)	Equivalent Load (kN/m)
1	Brick wall (Floors 2–3)	2.50	2.75	6.90

Table 8. Superimposed Dead Loads (SIDL) as Line Loads on Roof Slabs

No.	SIDL Line Loads on Roof Slabs	Load (kN/m^2)	Height (m)	Equivalent Load (kN/m)
1	Brick wall (Roof)	2.50	3.75	9.40

3. **Live Load**

   Live loads are temporary loads that vary in magnitude or position over time. They originate from human activities, movable objects, or equipment placed on the building structure, but do not include any permanent components of the structure itself.

Table 9. Live Loads

No.	Live Load Areas (Floors 2–3)	Load (kN/m^2)
1	Meeting Room	4.79
2	Staircase	4.79
3	Toilet	4.79

4. **Roof Live Load**

   The roof live load is a type of live load that specifically acts on the roof elements of a building. This load is not permanent in nature but may arise from temporary activities, human presence, equipment, or movable objects placed on the roof. The roof live load in this study was taken as 0.96 kN/m^2.

5. **Earthquake Load**

The calculation of earthquake loads referred to SNI 1727:2020, which governs the determination of seismic parameters for response spectrum analysis. Earthquake loads are defined as forces acting on a structure due to ground shaking during an earthquake, causing the building to vibrate. The response spectrum analysis of the existing church building was conducted using the following procedure:

a. **Seismic Importance Factor (Ie)**

The church building falls under Risk Category IV, with an importance factor of 1.5, as it is classified as a place of worship.

b. **Site Class**

The site class was determined from Standard Penetration Test (SPT) results and laboratory testing, as reported in the soil investigation for the Jakarta Gelora Marriott Hotel project. The upper layer, dominated by high-plasticity clay (CH), was classified as Site Class SE.

c. **Response Spectrum Parameters (Ss, S1)**

The response spectrum parameters were obtained by inputting the site coordinates into the official RSA website (https://rsa.ciptakarya.pu.go.id/2021/), yielding Ss = 0.7806 and S1 = 0.3823.

d. **Site Coefficients (Fa and Fv)**

The site coefficients were determined from Tables 6 and 7 of SNI 1727:2020. The values obtained were Fa = 1.399 and Fv = 2.470.

e. **Spectral Response Parameters**

The design spectral accelerations SDS and SD1 were calculated according to Equations (7) – (10) in SNI 1727:2020, as follows:

$SMS=Fa\times Ss=1.399\times 0.7806=1.092g$

$SM1=Fv\times S1=.470\times 0.3823=0.945g$

$SDS=23\times SMS=23\times 1.092=0.728g$

$SD1=32\times SM1=32\times 0.945=0.630g$

After determining the spectral acceleration parameters at 0 and 1 second, the characteristic periods T0 and Ts were computed as:

$T0=0.2\times SDSSD1=0.2\times 0.7280.630=0.17$ seconds

$Ts=SD1SDS=0.6300.728=0.86$ seconds

f. **Structural System**

Based on SNI 1727:2020, Clause 7.2.2, the structural system must satisfy seismic design category limitations and allowable building height. For the existing church building, the seismic-force-resisting system was modeled as a Special Moment Resisting Frame (SMRF), with the following coefficients:

Table 10. Seismic Force-Resisting System Factors

Parameter	Symbol	Value
Response modification coefficient	R	8
System overstrength factor	Ω	3

g. Structural Load

The load from the existing church building, located adjacent to the soldier pile installation area, was modelled as a uniform load. The total building load was obtained using ETABS V22, with input parameters consistent with field measurements. All calculations followed SNI 1729:2019 and SNI 1727:2020. The modelling results are shown in the following figure.

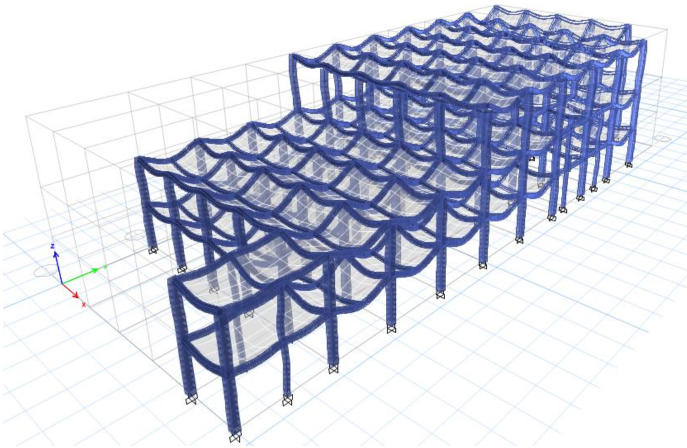


Figure 1. Structural Modelling of the Existing Church Building

h. Total Load

In this analysis, the maximum load of the existing church building was obtained as 2,480.415 kg/m^2, equivalent to 24.33 kN/m^2.

Table 11. Maximum Load of the Church Building.

Story	Mass (kN)	Floor Area (m^2)	kN × Floor Area	Unit
Roof	2137.19	343.2	6.23	kN/m^2
3rd Floor	5535.46	605.9	9.14	kN/m^2
2nd Floor	5434.75	605.9	8.97	kN/m^2
Jumlah	13107.40	**Total**	**24.33**	kN/m^2

Soldier Pile Modeling in PLAXIS 2D

This study was conducted in the context of the Jakarta Gelora Marriott Hotel construction project, located in West Jakarta. For the ramp foundation excavation, a soldier pile retaining system was employed because the excavation site was directly adjacent to the existing church building. The soldier piles used in the analysis had a diameter of 60 cm and a length of 8 m, including the pile cap. The geotechnical input parameters were derived from Standard Penetration Test (N-SPT) data.

The excavation depth (H) was 800 cm. With the installation of soldier piles, this study evaluated displacement, deformation, and the safety factor (SF). The analysis was performed using PLAXIS 2D V21 to determine whether the soldier pile system provided sufficient stability against the surrounding soil and whether the resulting safety factor satisfied the required criteria.

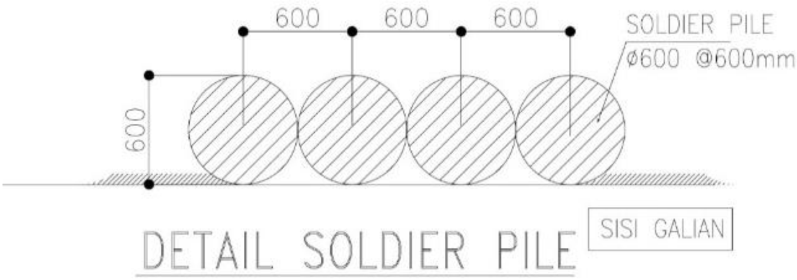


Figure 2. Plan View of the Soldier Pile

Table 12. Soil Parameters for PLAXIS 2D Modeling

Parameter	Symbol	Layer 1	Layer 2	Unit
Elastic Modulus	**E**	**3300**	**7800**	**kN/m²**
Poisson's Ratio	v	0.33	0.33	–
Cohesion	c	29	29	kN/m²
Friction Angle	ϕ	28	32.2	°
Dilatancy Angle	ψ	–	–	°
Saturated Unit Weight	γ_sat	17.30	18.6	kN/m³
Unsaturated Unit Weight	γ_unsat	16.30	18.5	kN/m³

In PLAXIS 2D V21, the soldier pile was modelled as a plate element, with thickness determined according to the stiffness properties calculated using the following equations:

Stiffness Properties

The stiffness properties are defined in terms of flexural stiffness (EI) and axial stiffness (EA). In plane strain modelling, EA is expressed as force per unit width, while EI is expressed as force multiplied by length squared per unit width. Therefore, the equivalent thickness of the plate element does not need to be manually specified, as it is automatically computed by the software based on these parameters. In this context, the model is assumed to have a unit width of one meter (b = 1 m), which is the standard assumption for two-dimensional plane strain analysis.

$$E = 4700\sqrt{fc'} \quad (1)$$

$$EI_{eq} = \frac{E(h_{eq})^3(b)}{12} \quad (2)$$

$$EA_{eq} = E(h_{eq})(b) \quad (3)$$

$$d_{eq} = h_{eq} = \sqrt{12\frac{EI}{EA}} \quad (4)$$

The Poisson's ratio used in this study was 0.20.

Unit Weight (w)

The unit weight of the plate was assigned as force per unit area, calculated according to the dimension (d) of the soldier pile:

$$w = \gamma_{concrete}(h_{eq}) \qquad (5)$$

Based on these calculations, the input parameters for soldier pile modeling in PLAXIS 2D V21 are summarized as follows:

Table 13. Soldier Pile Input Parameters for PLAXIS 2D Modeling

Parameter	Soldier Pile Value	Unit
Elastic Modulus, E	23,500	kPa
Flexural Stiffness, EI	149.5005404	kN·m^2/m
Axial Stiffness, EA	6644.468462	kN/m
Equivalent Thickness, d	0.519615	m
Unit Weight, w	12.47076581	kN/m^2
Poisson's Ratio, ν	0.20	-

Soldier Pile Modelling Procedure in PLAXIS

The modelling of soldier piles in PLAXIS software was carried out in the following sequence:

1. Soil Definition (Soil Tab)
   The soil and soldier pile materials were defined using the *Show Materials* tab. A *borehole* was then created to define the thickness of the soil layers vertically, in accordance with the soil stratigraphy and geometry.
2. Structural Definition (Structures Tab)
   The soldier pile retaining wall was modelled with a diameter of 60 cm, using concrete with a compressive strength of f'c=25MPa. Within the *Show Materials* tab, the material type was set to *Plate*, and the stiffness parameters (EI, EA), along with other pile properties, were entered. A polygonal geometry was then created under the *Structures* tab to represent the pile dimensions, and a uniform load was applied above the soil. The soil and soldier pile parameters previously defined were assigned to their respective geometries. Additionally, a line was drawn within the soil layers to mark the area designated for excavation of the ramp foundation.
3. Meshing
   The meshing stage, often referred to as discretization in finite element analysis, was performed to divide the geometry into finite elements. The resulting mesh configuration from the model is shown below.

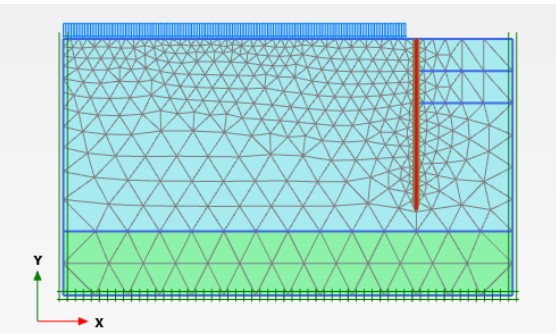


Figure 3. Meshing Element

4. Groundwater Modelling
   Before proceeding to the calculation stage, groundwater conditions were defined in the *Flow Conditions* tab. The distribution of pore water pressure was assumed to begin at the deepest excavation elevation of the ramp foundation, i.e., at a depth of 3 m below the original ground surface.
5. Stage Construction
   The final step in the analysis was conducted in the *Stage Construction* tab. This feature is a step-by-step simulation method used to model the construction process sequentially, in accordance with site conditions, with the purpose of capturing the soil and structural responses accurately under changing construction activities.

In this study, two excavation stages were modelled, reaching a total depth of 3 m for the ramp foundation. At each stage, the Safety Analysis option was activated, and the Reset Displacements to Zero feature was applied. The purpose of this setting was to evaluate the safety factor at each stage. The *Calculate* function was then executed to perform the analysis. If the input parameters were consistent, the phase indicator turned green. Conversely, a red indicator signaled inconsistencies between the soil parameters and the soldier pile parameters.

Results of Soldier Pile Retaining Wall Analysis

In this study, the analysis was performed using plastic (short-term) analysis. The evaluation focused on the magnitude of deformation, lateral displacement, and the forces acting within the soil to resist the imposed loads. The following presents the results of the short-term (plastic) analysis based on the effective soil parameters.

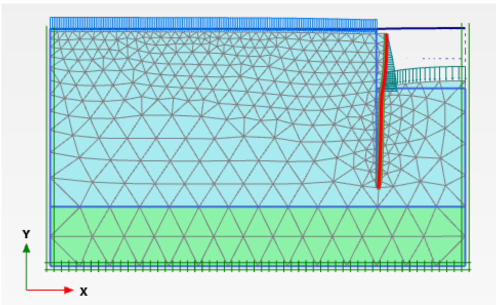


Figure 4. Deformation Magnitude in Second Excavation Stage

From the plastic analysis output (Figure 4), the maximum deformation during the second excavation stage was found to be 0.05659 m (56.59 mm), occurring beneath the existing church structure.

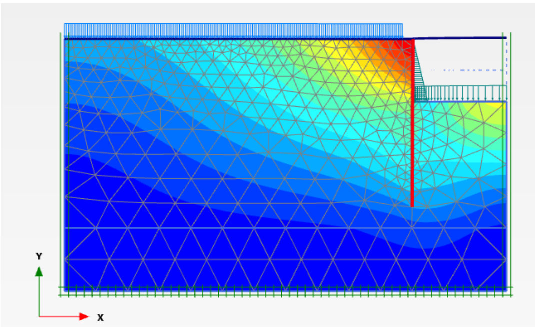
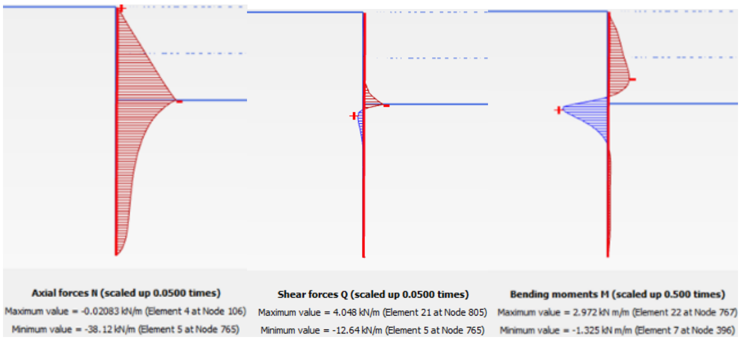


Figure 5. Displacement Magnitude in Second Excavation Stage

From the plastic analysis output (Figure 5), the maximum lateral displacement during the second excavation stage was found to be 0.05819 m (58.19 mm).

From the plastic analysis output (Figure 6), the axial force acting on the soldier pile was –38.12 kN/m, the shear force was 4.04 kN/m, and the bending moment was 2.97 kN/m**.**



(a) (b) (c)

Figure 6. Axial Force (a), Shear Force (b), and Bending Moment (c) on Soldier Pile

Figure 7. Plastic Analysis Output of Soldier Pile

Excavation Stage	**Total Displacement (mm)**	**Displacement X (mm)**	**Displacement Y (mm)**	**Axial Force (kN/m)**	**Shear Force (kN/m)**	**Bending Moment (kN·m/m)**
1	33.33	31.41	31.43	–18.21	–9.334	1.880
2	58.19	53.45	37.54	–38.12	–12.64	2.972

Based on Table 18, the first excavation stage produced a total displacement of 33.33 mm, with lateral displacements of 31.41 mm in the X-direction and 31.43 mm in the Y-direction. The axial force at this stage was –18.21 kN/m, the shear force was –9.334 kN/m, and the bending moment was 1.880 kN·m/m.

During the second excavation stage, the total displacement increased significantly to 58.19 mm, with displacements of 53.45 mm in the X-direction and 37.54 mm in the Y-direction. The axial force increased to –38.12 kN/m, the shear force to –12.64 kN/m, and the bending moment to 2.972 kN·m/m. This increase in displacement, internal forces, and bending moments at the second stage indicates that deeper excavations result in higher lateral loads acting on the soldier pile, highlighting the need for careful consideration of wall stability in design.

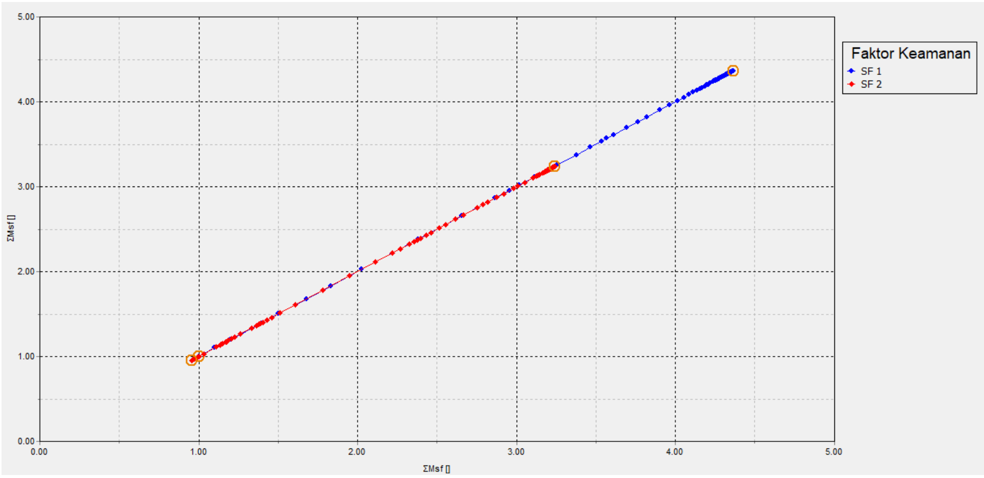


Figure 8. Safety Factor at Excavation Stages 1 and 2

From the short-term (plastic) analysis, the safety factor for the first excavation stage was 4.1**,** while the safety factor for the second excavation stage was 3.2**.**

Table 14. Safety Factor Results

Depth Range (m)	Excavation Stage	Safety Factor (SF)	Remarks
0 – 1.5	1	4.33	> 2, safe
1.5 – 3.0	2	3.23	> 2, safe

As shown in Table 16, for the first excavation stage (0–1.5 m depth), the safety factor was 4.33, indicating excellent stability against overturning. This value far exceeds the minimum recommended safety factor of 2 as stipulated in geotechnical design standards, confirming that the retaining system was safe and stable under lateral soil loads. For the second excavation stage (1.5–3.0 m depth), the safety factor was 3.23, which, although lower than the first stage, still remained well above the required minimum.

Table 15. Comparison of Analysis Output with SNI 8460:2017 Limits

Parameter	Analysis Result	SNI 8460:2017 Limit
Displacement	58.19 mm	< 40 mm
Deformation	56.59 mm	< 40 mm
Safety Factor (SF)	3.23	> 2

As shown in Table 20, both displacement and deformation exceeded the allowable limit of 40 mm specified in SNI 8460:2017. However, the safety factor values satisfied the requirement, remaining well above the minimum of 2.

It is important to note that in geotechnical analysis, the relationship between the soil's elastic modulus and cohesion cannot be directly correlated. Cohesion significantly influences the safety factor, while the elastic modulus primarily affects soil displacement. In this case study, the relatively high cohesion values contributed to a safety factor well above the minimum requirement, while the low elastic modulus resulted in excessive displacements beyond the allowable limits.

A practical improvement solution would be to increase the stiffness of the soldier pile system, for example by enlarging the pile diameter from 60 cm to 80 cm, or by installing additional supports/anchors to enhance lateral resistance.

CONCLUSION

Based on the results of the analysis and research conducted, the following conclusions can be drawn:

1. The safety factor values of the soldier pile reinforcement system were evaluated for two excavation stages of the ramp foundation. The safety factor for the first excavation stage was 4.3, while for the second excavation stage it was 3.2. Both values satisfied the requirements of SNI 8460:2017, which specifies a minimum safety factor of 2 for permanent retaining structures (Badan Standardisasi Nasional, 2017).
2. The displacements of the soldier pile retaining wall were assessed in two excavation stages, with results presented as total displacement, displacement in the X-direction, and displacement in the Y-direction. In the first excavation stage, the total displacement was 33.33 mm, with 31.41 mm in the X-direction and 31.43 mm in the Y-direction. In the second excavation stage, the total displacement increased to 58.19 mm, with 53.45 mm in the X-direction and 37.54 mm in the Y-direction.

The corresponding deformations were 33.34 mm in the first stage and 56.59 mm in the second stage. The lateral deflection of the retaining wall in the second stage reached 58.19 mm, exceeding the maximum allowable limit of 40 mm as specified in SNI 8460:2017. The excess of 18.19 mm indicates that the deflection criteria were not satisfied, potentially resulting in excessive lateral movement.

An optimal remedial measure would be to increase the stiffness of the soldier pile system, for example, by enlarging the pile diameter from 60 cm to 80 cm and installing additional supports or anchors to enhance lateral resistance.

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