(e)ISSN 2656-8896 (p)ISSN 2656-890X
Journal of Infrastructure and Facility Asset Management – Vol. 7, Issue 1, January 2025

A Study of Pile Displacement in Soft Soil: The Case of Semarang - Demak Toll Road Construction Package 1B

Novera Sagita[1,a], Herman Wahyudi[2,b], Yudhi Lastiasih[3,c) & Yusrizal Kurniawan[4,d]

[1)] *Magister Student, Civil Engineering Dept, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia*
[2,3)] *Civil Engineering Department, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia*
[4)] *National Road Implementation Agency of Central Java-Yogyakarta Region, Directorate General of Highways, Ministry of Public Works, Indonesia*

Correspondent : [a)]sagitanovera@gmail.com, [b)]herman_its@yahoo.com, [c)]yudhi.lastiasih@gmail.com & [d)]yusrizal.kurniawan@pu.go.id

ABSTRACT

In the construction package of Semarang-Demak Toll Road 1B, an elevated bridge is planned to be built using a pile foundation of 56 pieces with a diameter of 1.0 m installed at a depth of 68m. The soil conditions at the site are very soft to medium clay and silt. During the excavation of the footing work, there was a displacement of 11 piles. This study aims to analyze the pile displacement behavior at each work sequence due to the influence of excess pore pressure and excavator distance near the pile. The pile displacement behavior was modeled using a Finite Element Method (FEM) based program, Plaxis 2D. Piles are modeled using an elastic constitution model to obtain deformation results that match the actual conditions in the field. While the soil is modeled using the Mohr Coulomb soil constitutive model on the embankment soil and Soft Soil on the original soil. The analysis was conducted to determine the lateral displacement of poles in field conditions at each sequence of work on unconsolidated soil with/without an excavator load of 15 kN. The results showed that by conditioning the soil at 90% consolidation degree (U90%) can reduce the lateral displacement value of the pile by 95.96% at the 4 m deep excavation stage compared to the unconsolidated soil. By placing the excavator 6.5 m away from the piles, it can reduce the lateral displacement that occurs by 20.96% compared to the existing position of 3.5 m from the piles.

Keywords : soft soil, spun pile, excavation, excess pore pressure, excavator load, lateral displacement.

INTRODUCTION

The Semarang-Demak Toll Road project is part of a toll road system that connects Semarang City and Demak City. In the Semarang-Demak Toll Road Development Package 1B, a 392-meter-long overpass is planned to be built from STA 1+578 to STA 1+970. This elevated bridge will be built using pile foundations. The project includes 27 piles consisting of groups of concrete piles with a diameter of 1 meter and a depth of 50-70 meters, located along STA 1+578 to STA 1+970 (Figure 1).

Soil conditions at STA 1+578 to STA 1+970, based on the results of soil investigations, consist of very soft to medium soil (compressible layer) with the soft soil thickness of approximately 25-40 meters. At the location of Pier 21, based on BH-5 data, the N-SPT values are as follows: less than 1 at 0-20 meters depth, 1-14 at 20-40 meters depth, 9-14 at 40-60 meters depth, and 13-23 at 60-80 meters depth (Figure 2). The existing soil in the Pier 21 area consists of pond soil. Therefore, a 3-meter-high embankment was constructed for the access road and to facilitate construction methods.

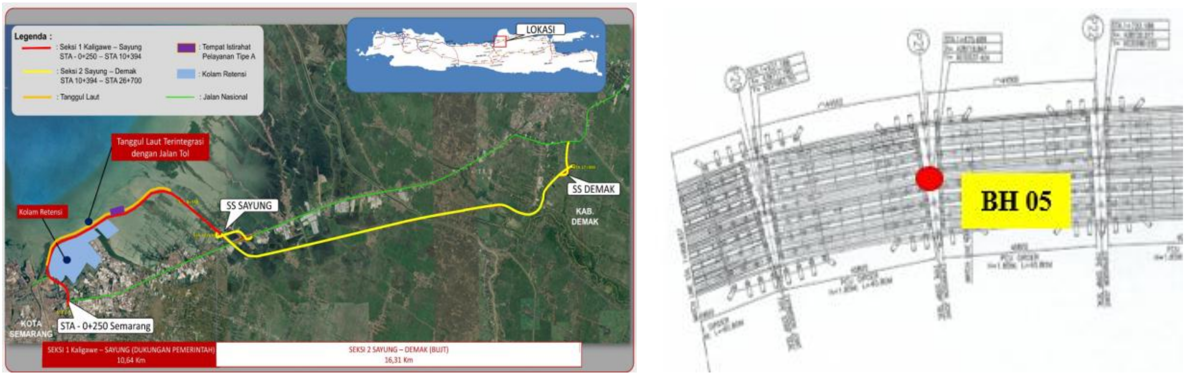


Figure 1. Location Map of Semarang – Demak Toll Road Project 1B

Source : BBPJN Central Java – Yogyakarta, 2024

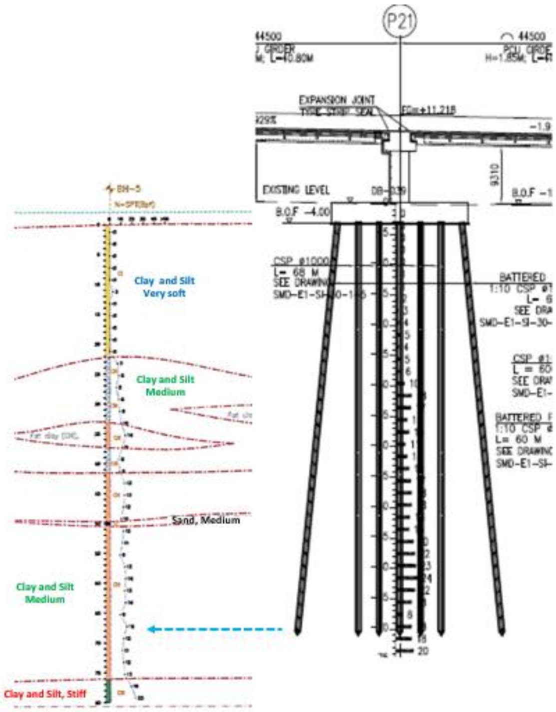
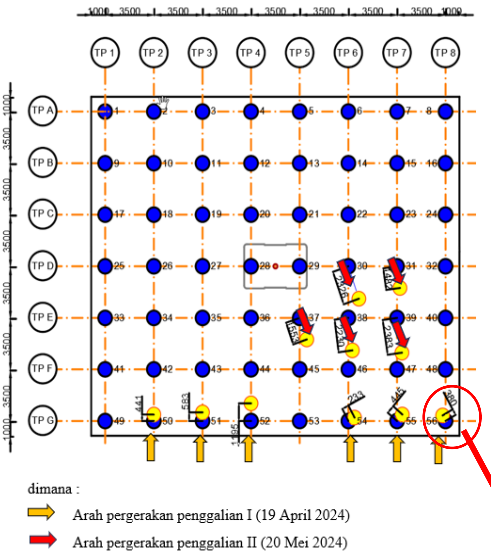


Figure 2. Location of *Pier 21* at Semarang – Demak Toll Road Project 1B
Source: BBPJN Central Java – Yogyakarta, 2024

At Pier 21, concrete piles with a diameter of 1.0 m were driven to a depth of 68 m. The pile driving process for Pier 21 proceeded smoothly as planned. However, during the excavation for the Pier 21 footing, which was planned to be embedded 4 m below the existing ground level with an excavation depth of 3.5 m, an issue arose with the displacement of several pile points. As shown in Figure 3, a total of 11 piles have shifted displacement, namely piles numbered 30, 31, 37, 38, 39, 50, 51, 52, 54, 55, and 56. The displacement occurred during the excavation for the footing, conducted on April 19, 2024, and May 20, 2024 (Figure 4). Therefore, an investigation is needed to study the behavior of the piles at each stage of construction to determine the cause of the displacement.



Poin Number	Horizontal Displacement (mm)	Allowable Horizontal Displacement (mm)
30	2.326	25,00
31	1.482	25,00
37	1.553	25,00
38	1.936	25,00
39	2.327	25,00
50	461	25,00
51	583	25,00
52	1.195	25,00
54	233	25,00
55	445	25,00
56	380	25,00

Figure 3. Pile Shiffting in *Pier 21* at Semarang – Demak Toll Road Project 1B
Source: BBPJN Central Java – Yogyakarta, 2024

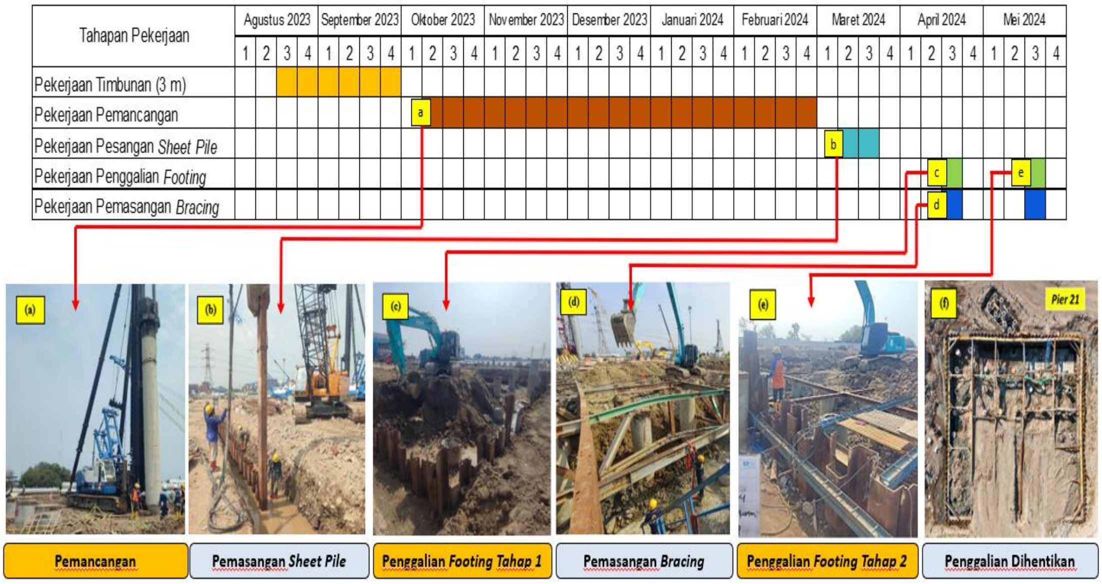


Figure 4. Pile Shiffting in *Pier 21* at Semarang – Demak Toll Road Project 1B
Source : BBPJN Central Java – Yogyakarta, 2024

LITERATUR REVIEW

Soft Soil

Soft soils are classified as cohesive soils, which are clays or silts that have a standard penetration value (SPT) of N less than 5 (Bowles, 1984 and Burt Look, 2007). Soft soils are characterized by low strength, low cohesion, low internal angle friction, low permeability, high deformation, and high plasticity. (Dyah Rahmawati, 2018). In addition, there is a correlation between N-SPT and undrained cohesion values as shown in the following Table 1.

Table 1. Correlation for Clay Parameters

Consistency	Cohesion not undrained, cu (kPa)	Conus resistance qc (kPa)	N SPT	Su (kPa)	Free compressive strength, qu (kPa)
Very soft	< 12,5	0 – 180	< 2	< 12	< 25
Soft	12,5 – 25	180 – 375	2 – 4	12 – 25	25 – 50
Firm	25 – 50	375 – 750	4 – 8	25 – 50	50 – 100
Stiff	50 – 100	750 – 1500	8 – 15	50 – 100	100 – 200
Very stiff	100 – 200	1500 – 3000	15 – 30	100 – 200	200 – 400
Hard	> 200	> 3000	> 30	> 200	> 400

Source : Ministry of Public Works, 2024

Concrete Pile Foundation

A pile foundation is part of a construction made of wood, concrete, and/or steel that is used to transmit surface loads (upper structure) to the ground (Bowles, 1984). According to its displacement, piles are divided into 3 categories, namely piles with large displacement in the form of solid/hollow piles whose ends are closed into the ground, small displacement piles in the form of solid/hollow piles whose ends are open into the ground and piles without displacement in the form of piles installed into the ground which are installed by digging/drilling into the ground (Hadiyatmo, 2023).

Lateral Loads on Piles

In addition to being designed to withstand vertical forces, pile foundations must be designed to withstand lateral forces that occur on them. Wahyudi H (1999) in the book Daya Dukung Pondasi Dalam states that this phenomenon can occur if there is a significant horizontal displacement (lateral movement) of the soil, because of the load of embankments/fills (embankments, reclamation, etc.) on top of soft soil layers (compressible soil). The lateral force that occurs on the pile depends on the stiffness/type of the pile, the type of soil, the embedment of the pile tip in the pilecap, and the amount of deflection (Hardiyatmo, 2023).

Excavation on Soft Soil

Excavation can cause both vertical and lateral ground movement, with lateral movement generally considered more critical for pile groups, especially concrete piles. This is because concrete piles are generally designed to withstand vertical compressive loads from above and have less capacity to withstand significant lateral loads. As a result, lateral ground movement due to excavation can cause excessive bending of the pile, cracking or even breaking, which can endanger the stability of the entire structure. The key factors influencing the response of a single pile are the excavation depth, excavation retaining conditions, soil properties, and pile properties (H.G. Paulos et al, 1997).

The deeper the excavation, the deeper the location where the maximum bending moment occurs on the pile. This indicates that the load supported by the pile is greater and more concentrated at the bottom of the pile (San-Shyan Lin et al, 2010). This means that the inclined piles are weaker in resisting existing lateral forces than the vertical piles (Sholech Nur et al, 2023).

The behavior of piles in bearing lateral loads is categorized into two conditions, namely active pile and passive pile. According to Li et al (2021), piles with lateral loads that occur directly on the pile head are categorized as active piles and piles that have lateral soil movement are categorized as passive piles. Excavation work will cause lateral soil movement that will push the surrounding piles so that this condition is categorized as a passive pile condition.

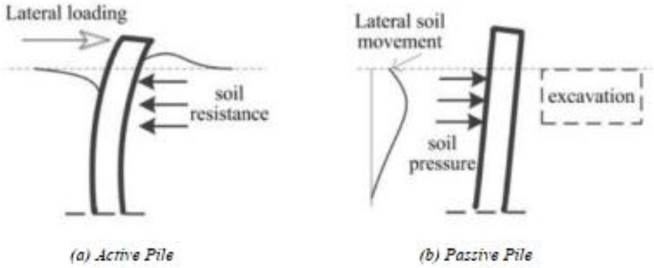


Figure 5. Perilaku tiang terhadap beban lateral

Source : Li et al, 2021

The more distant the pile is from the excavation site, the smaller the pile response to ground motion. The response of the pile to maximum moment and deflection decreases exponentially with distance from the excavation (Leung et al, 2000). The piles made before excavation will have greater lateral movement as the soil has not consolidated as the piles made after excavation (Pham et al, 2020).

Effect of Excess Pore Pressure on Lateral Displacement

Lateral displacement of piles due to hydrostatic stress is a phenomenon in which piles experience shifting or deformation due to water pressure in the soil. This hydrostatic stress can affect the stability and strength of piles, especially in water-saturated soil conditions. The deeper the pile, the greater the hydrostatic pressure that must be withstood (Indrasurya, 2023). When excavation is carried out, the excess pore water pressure is lost because the load of the embankment is removed so that only hydrostatic pressure remains, resulting in a difference in pore water pressure (ΔU) which results in lateral movement of the soil from the high-pressure area to the lower-pressure area.

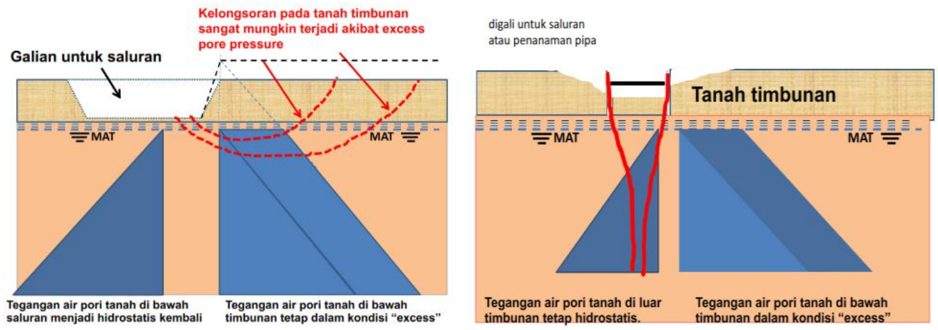


Figure 6. Illustration of collapse of embankment due to excess pore pressure

Source : Indrasurya B. Mochtar, 2023

Effect of Heavy Equipment on Lateral Displacement

The excavation and heavy equipment load on the soft soil surrounding the piles cause lateral movement of the soil which creates passive pressure on the pile foundation so that it is displaced. In the unexcavated field condition, the greater the distance between the load and the pile, the greater the lateral soil movement. (Mawarni, 2023).

RESEARCH METHOD

The research methods used were collecting secondary data such as soil test results and pile displacement data, literature studies related to pile displacement, and field reviews to observe actual conditions. The pile displacement behavior was modeled using a Finite Element Method (FEM) based program, Plaxis 2D, to simulate the excavation process and analyze the behavior of soil and piles. By comparing the results of the numerical analysis with the field conditions, the authors were able to identify the factors that cause pile displacement, such as soil conditions, implementation methods, and environmental influences. The analysis included lateral soil deformation, excess pore pressure, and bending moment at each sequence of construction.

DATA COLLECTION

In this research, the soft soil used is in accordance with what is in the case study location, namely the Semarang - Demak Toll Road Construction Project Section 1B at BH-05. This data will then be used in modeling using the Back Calculation method to obtain lateral displacement values that are the same as the actual conditions in the field. The other data related to material specifications and materials are taken from the catalog of products used by Wijaya Karya (Persero) Tbk.

Table 2. Soil Parameter on Modelling (*Back Calculation Plaxis 2D)*

Parameter		Initial Soil							
		0 - 20 m	20 - 35 m	35 - 46 m	46 - 49 m	49 - 51 m	51 - 58 m	58 -75 m	75 - 80 m
Modelling		Mohr Coulomb							
		Soft Soil	Soft Soil	Soft Soil	Soft Soil	Soft Soil	Soft Soil	Soft Soil	Soft Soil
Drainage Type		Undrained A	Undrained A	Undrained A	Undrained A	Undrained A	Undrained A	Undrained A	Undrained A
Soil Description		Inorganic Clay and Silt	Inorganic Clay and Silt	Inorganic Clay and Silt	Inorganic Clay and Silt	Sand and Silt	Inorganic Clay and Silt	Inorganic Clay and Silt	Inorganic Clay and Silt
Consistency		Very Soft	Medium	Medium	Medium		Medium	Medium	Stiff
Relative Density						Medium			
Dry Volume Weight (γ_d)	kN/m^3	8,00	8,70	12,30	12,20	12,20	12,20	12,30	12,30
Saturated Volume Weight (γ_{sat})	kN/m^3	14,30	14,60	17,00	17,00	17,00	17,00	17,20	17,20
Unsaturated Volume Weight (γ_t) =(γ_{unsat})	kN/m^3	14,30	14,50	16,90	16,80	16,80	16,80	17,00	17,00
Water Volume Weight (γ_w)	kN/m^3	10,00	10,00	10,00	10,00	10,00	10,00	10,00	10,00
Gs		2,56	2,50	2,61	2,55	2,55	2,55	2,61	2,61
e		2,22	1,88	1,12	1,10	1,10	1,10	1,12	1,12
Young's Modulus (Es)	kN/m^2	2.000	15.000	15.000	15.000	5.000	15.000	15.000	50.000
Poisson Ratio (V ur)		0,20	0,11	0,11	0,13	0,13	0,13	0,15	0,15
Internal Angle Friction (ø')		17,00	17,00	18,00	18,00	18,00	22,00	22,00	22,00
Effective Cohesion (c')	kN/m^2	3,30	1,20	2,50	2,50	2,30	2,30	6,50	6,50
K0 determination		Automatic	Automatic	Automatic	Automatic	Automatic	Automatic	Automatic	Automatic
Modified Compression Index (λ)		0,20	0,20	0,11	0,11	0,13	0,13	0,15	0,15
Modified Swelling Index (κ)		0,02	0,02	0,04	0,04	0,04	0,03	0,03	0,03

Table 3. Soil Parameter on Modelling for Embankment Material

Parameter		Soil Embankment +3 - 0 m	Foundation Material Spun Pile
Modelling		Mohr Coulomb	Linear Elastic
		Mohr Coulomb	Non-Porous
Drainage Type		Drained	Embedded Beam
Soil Description		Gravel, Sand and Silty	
Consistency		Medium	
Relative Density			
Dry Volume Weight (γ_d)	**kN/m^3**	14,81	
Saturated Volume Weight (γ_{sat})	**kN/m^3**	16,00	24,00
Unsaturated Volume Weight (γ_t) =(γ_{unsat})	**kN/m^3**	16,50	24,00
Water Volume Weight (γ_w)	**kN/m^3**	10,00	
Gs		2,67	
e		0,80	
Young's Modulus (Es)	**kN/m^2**	20.000	33.892.182
Poisson Ratio (Vur)		0,30	0,15
Internal Angle Friction (ø')		32,00	

Table 4. Sheet Pile Parameter on Modelling

Parameter *Sheet Pile*	**JIS III**	**JIS IV**
Material Type	Elastic	Elastic
E (kN/m^2)	200.000.000,00	200.000.000,00
v	0,15	0,15
I (m^4)	0,000168	0,000386
A (m^2)	0,0191	0,0243
EA (kN/m)	3.820.000,00	4.850.000,00
EI (kN/m)	33.600,00	77.200,00

Table 5. Bracing Strut Parameter on Modelling

Parameter *Bracing (Strut)*	**H Beam 150.150.7.10**
Material Type	Elastic
E (kN/m^2)	200.000.000,00
L *Spacing* (m)	5,80
A (m^2)	0,0040
EA (kN/m)	802.400,00

RESEARCH ANALYSIS

Structure Modeling on Each Sequence of Work

The clay layer in this model is assumed to behavior according to the Soft Soil model, which is a common model in soil mechanics. The undrained condition of the clay layer indicates that the water in the soil pores cannot drain out quickly when the pile is loaded. This increase in pore pressure will reduce the effectiveness of the stress held by the soil, thereby reducing the bearing capacity of the piles. The sand backfill layer will be modeled using the Mohr Coulomb model. Undrained conditions are also assumed in the sand layer due to rapid loading. In the modeling, the soil is assumed to be unconsolidated.

The focus in this modeling is to determine the behavior of the pile foundation and obtain information about the lateral displacement of the pile, the effect of excess pore pressure behavior at each sequence of implementation and the effect of excavator distance around the pile. The modeling was reviewed from post-driving of piles to 4 m deep excavation works. At the 1 m excavation stage, horizontal stiffeners (strut) at a depth of 0.5 m and 2.0 m were installed.

Table 6. Summary of Structure Modelling on Each Sequence of Work

Observed Behavior	Driving Spun Pile	Sheet Pile	Excavation 1 m	Excavation 2 m	Excavation 3 m	Excavation 4 m
Excess Pore Pressure **(kN/m^2)**	93,000	90,300	91,690	101,500	102,540	111,700
Lateral Displacement – on 56th Pile (Ux) (m)	0,006	0,010	0,014	0,014	0,015	0,371
Bending Moment – on 56th Pile **(kNm)**	77,330	102,030	107,800	112,600	172,500	2.538,000

From **Error! Reference source not found.**, it can be inferred that excavation increases the water pressure in the soil pores due to reduced soil pressure. The excavation disturbed the equilibrium of pore water pressure in the soil. The piles had significant displacement during the excavation activity, especially at the 4 m deep excavation stage. The excavation activities reduced the soil support of the pile, causing the pile to move more easily. The maximum lateral movement occurred during the 4 m deep excavation, the movement was 0.3713 m (Plaxis 2D modeling), which is close to the actual movement in the field of 0.380 m. The bending moment acting on Pile 56 fluctuated significantly during the excavation process. This increase in bending moment causes over-stress on the pile and damage because it has already exceeded its resistance limit. The bending moment that occurs according to Plaxis 2D modeling is = 2,538 kNm, which is greater than the Moment Break value of 1,890 kNm.

Effect of Excess Pore Pressure on Pile Displacement

In general, excavation activities create conditions where the pore water pressure of the soil will be trying to find its equilibrium state. The pressure will naturally move from high pressure areas to low pressure areas. The activity of backfilling in soft clay causes excess pore pressure because consolidation has not yet occurred and takes a prolonged period.

Table 7. The Result of Structure Modelling on Each Sequence of Work

	Excess Pore Pressure Equivalent in P		**Lateral Displacement**	
	Without Consolidation (kN/m)	**With Consolidation (U90%) (kN/m)**	**Without Consolidation (m)**	**With Consolidation (U90%) (m)**
Driving Spun Pile	3.140,00	508,70	0,005	0,014
Driving Sheet Pile	3.103,00	516,80	0,010	0,015
Excavation 1 m	3.072,00	446,50	0,015	0,015
Excavation 2 m	2.978,00	1.112,00	0,014	0,015
Excavation 3 m	3.502,00	1.151,00	0,015	0,015
Excavation 4m	4.050,00	1.105,00	0,371	0,015

Excavation disturbs the equilibrium of existing stress, resulting in differential stresses in the soil. In the excavation area the soil stress is reduced, so the pressure will move from the high-pressure area to the low-pressure area. This movement causes heave around the excavation area which gives pressure on the pile. The amount of heave pressure that occurs on pile 56 in the existing condition is equivalent to a P force of 4,050 kN. This pressure caused the pile to be displaced to the right by 0.371 m from its initial position as shown in Table 7.

To determine the effect of excess pore pressure, a modeling variation was performed assuming the soil had consolidated to 90% consolidation degree. In Plaxis 2D modeling, it was found that the lateral displacement value of the piles can be reduced by 95.96% at the 4 m deep excavation stage. This reducing effect is not linear along with the depth of excavation as shown in Figure 7.

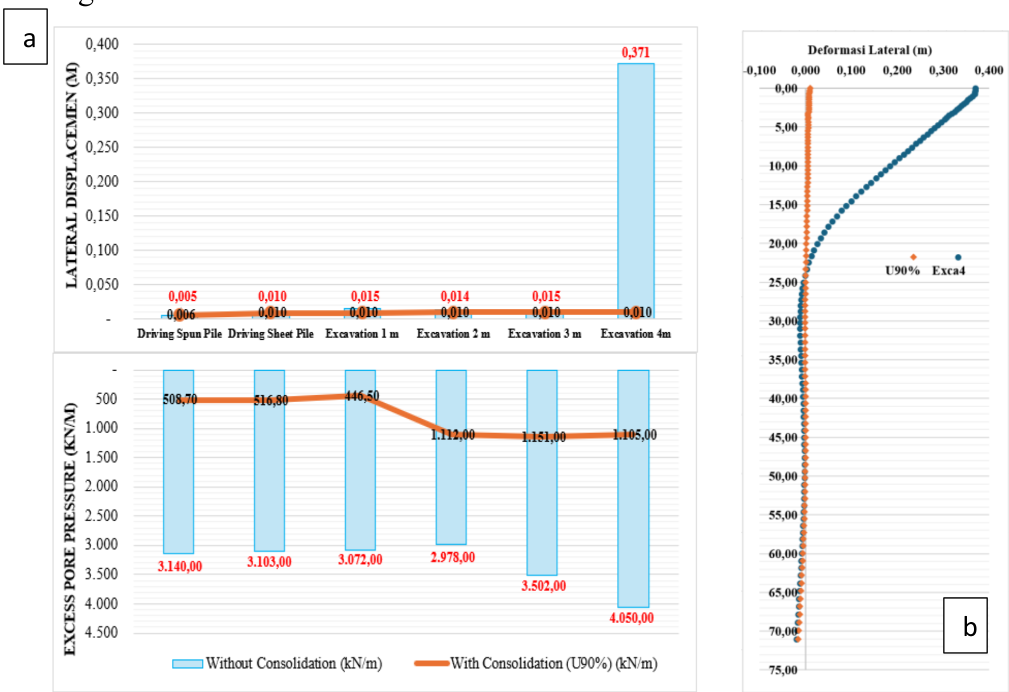


Figure 7. Relationship of Lateral Displacement with The Effect of Excess Pore Pressure at Each Sequence of Work (A); Relationship of Lateral Displacement at 56th Pile (Excavation 4 M) at Each Depth in Conditions Before and After Consolidation (B).

(e)ISSN 2656-8896 (p)ISSN 2656-890X
Journal of Infrastructure and Facility Asset Management – Vol. 7, Issue 1, January 2025

Effect of Excavator Distances on Lateral Displacement

To identify the effect of excavator position on lateral displacement of piles, 3 comparison models were made with the Plaxis 2D application. The modeling is soil modeling with no excavator in the excavation area, modeling with the excavator distance position of 3.5 m from pile 56, and modeling with the excavator distance position of 6.5 m from pile 56. The modeling results are shown in Table 8 and Figure 8.

Table 8. The Result of Structure Modeling Depend on Distance of Excavator

Structure Modeling	Lateral Displacement Ux (m)
Without Excavator	0,097
Distance of Excavator 6,5 m from 56th Spun Pile	0,293
Distance of Excavator 3,5 m from 56th Spun Pile	0,371

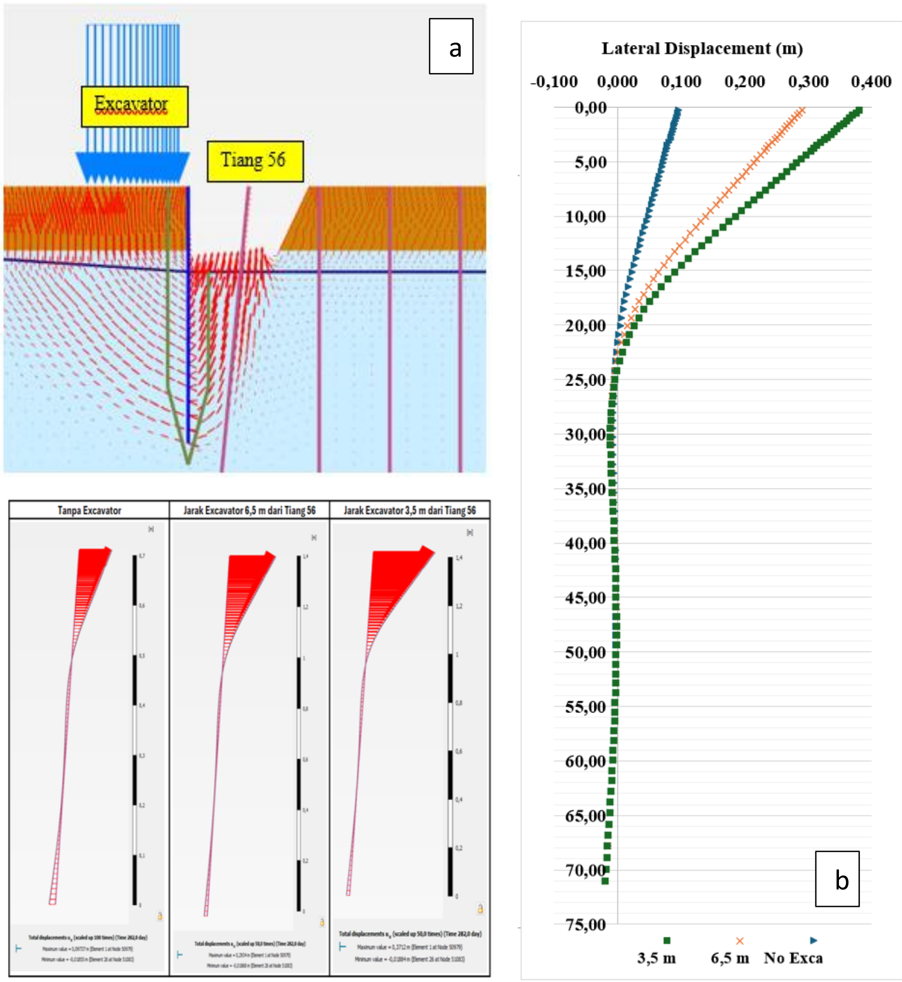


Figure 8. Plaxis Modeling with Excavator around The Excavation Area (A); Lateral Displacement Relationship at 56th Pile (Excavation 4 M) at Each Depth with Variation in Excavator Position Distance (B)

It can be concluded that the position of the excavator has a significant influence on the displacement of the pile. The closer the excavator position to the pile, the more the lateral displacement value increases. By positioning the excavator 6.5 m away from the piles, it can reduce the lateral displacement that occurs by 20.96% compared to the existing position of 3.5 m from the piles. This reducing effect is not linear with the distance of the excavator position.

CONCLUSIONS

Based on the results of the analysis and calculations presented in the previous chapter, the following points can be concluded:

1. Each sequence of construction affects changes in soil response to the structure.
2. The differences in excess pore pressure at each stage of excavation affect the lateral displacement and bending moment of the piles. The deeper the excavation depth, the more heave value increases. The deeper the excavation depth, the more the lateral displacement value increases as the bending moment of the pile increases but this increase is not linear.
3. Soil consolidation plays a significant role in reducing the lateral displacement value of piles. By conditioning the soil at 90% consolidation degree (U90%), it can reduce the lateral displacement value of piles by 95.96% at the 4 m deep excavation stage than the unconsolidated soil. This reduction effect is not linear with the depth of excavation.
4. The more the distance of the pile is from the excavator position, the more the lateral displacement value decreases. By placing the excavator 6.5 m away from the pile, it can reduce the lateral displacement by 20.96% compared to the existing position of 3.5 m away from the pile. This reduction effect is not linear with the distance of the excavator position.

REFERENCES

[1] Ardana, M.D. & Mochtar, I.B. (1999). *Pengaruh Tegangan Overburden Efektif dan Plastisitas Tanah terhadap Kekuatan Geser Undrained Tanah Lempung Berkonsistensi Sangat Lunak Sampai Kaku yang Terkonsolidasi Normal*. Jurusan Teknik Sipil FTSP – ITS. Surabaya.

[2] Badan Standarisasi Nasional (2017). S*NI 8460:2017 Persyaratan Perancangan Geoteknik.* BSN. Jakarta.

[3] Bowles, J.E. (1991). *Buku Analisis dan Desain Pondasi Jilid I Edisi ke-4*. Erlangga. Jakarta.

[4] Bowles, J.E. (1991). *Buku Analisis dan Desain Pondasi Jilid II Edisi ke-4*. Erlangga. Jakarta.

[5] Chong, M.K. (2013). *Soil Movement Due to Displacement Pile Driving*. International Conference on Case Histories in Geotechnical Engineering: Page 30.

[6] Das, B. M. (1988). *Principle of Geotechnical Engineering*. The University of Texas. Texas.

[7] Hardiyatmo, H.C. (2002). *Mekanika Tanah I*. Gajah Mada University Press.

[8] Hardiyatmo, H.C. (2003). *Mekanika Tanah II*. Gajah Mada University Press.

[9] Hwang, J.H. Neng Liang, dkk. (2001). "Ground Response During Pile Driving". *Journal of Geotechnical and Geoenvironmental Engineering: Page 940.*

[10] Leung, C. F., Chow, Y. K. & Shen, R. F. (2000). "Behavior of Pile Subject to Excavation-Induced Soil Movement". *Journal of Geotechnical and Geoenvironmental 1 Engineering, 126(11), 947-954.*

[11] Lin, C., Huang. L, dkk. (2023). *Study on Shielding Effect of The Pile Group in a Soft-Soil Fondation*. MDPI. Switzerland.

[12] Lin, San-Shyan, Jen-Cheng Liao, dkk. (2010). *A Case Study of Drilled Shaft Performance from Excavation Induced Slope Movements*. Geotechnical Special Publication. National Taiwan Ocean University.

[13] Massarsch, K.R and C. Wersall. (2013). *Comulative Lateral Soil Displacement Due to Pile Driving in Soft Clay*. Sound Geotechnical research to Practice. Honouring Robert D. Holtz II, ASCE. Pp. 463-480.

[14] Maylda, Gumbert and Agus Darmawan, dkk (2018). "Pengaruh Pemancangan Fondasi Tiang pada Tanah Lempung Jenuh Terhadap Tekanan Air Pori". *Jurnal Teknik Sipil : Vol. 14, No. 4.*

[15] Mawarni, Sianturi (2023). *Analisis Pergeseran Lateral Tiang Pancang pada Tanah Lempung Akibat Galian dan Beban Konstruksi Menggunakan Metode Elemen Hingga (MIDAS GTS NX)*. Fakultas Teknik Sipil Universitas Indonesia.

[16] Mochtar, Indrasurya B. *Permasalahan Geoteknik pada Pembangunan di Lahan Basah*. ITS. Surabaya.

[17] Nur, Sholech, Sito Ismanti, dkk. (2023). "Evaluation of Inclined Piles Due to Driving in Soft Soil". *ICST UGM 2023: E3S Web of Conferences 468.*

[18] Ou, Xuefeng dan Xiangcu Zheng, dkk (2024). "Large deformation problems arising from deep excavation in silt strata: A case study in Shenzhen, China". *Journal of Rock Mechanics and Geotechnical Engineering: Chinese Academy of Science.*

[19] Patria, Adhe Noor. (2008). *Analisis Perubahan Tekanan Air Pori Pada Tanah Lunak di Bawah Piled – Geogrid Supported Embankment*. Media Telekomunikasi Ilmiah di Bidang Teknik Sipil : Vol 9, No. 2.

[20] Poulos, H.G. (1976). *Behaviour Of Laterally Loaded Piles Near A Cut Or Slope*. The University of Sidney. Sidney.

[21] Poulos, H.G. and I Fellow, dkk (1997). "Pile Response Due to Excavation-Induced Lateral Soil Movement". *Journal of Geotechnical and Geoenvironmental Engineering.*

[22] Small, J. C., Poulos, H. G., Nguyeni, V. D., Small2, J. C., & Poulos3, H. G. (2005). "Effect of soil movements due to excavation on piled foundations". *Journal of the Southeast Asian Geotechnical Society.*

[23] U.S. Department of Transportation Federal Highway Administration. (2016). *Design and Construction of Driven Pile Foundation – Volume I*. National Highway Institute.

[24] U.S. Department of Transportation Federal Highway Administration. (2018). *Drilled Shafts: Construction Procedures and Design Methodes*. National Highway Institute.

[25] Wahyudi, H. (1999). *Daya Dukung Pondasi Dalam*. Jurusan Teknik Sipil, Fakultas Teknik Sipil dan Perencanaan, Institut Teknologi Sepuluh Nopember. Surabaya.

[26] Wersall, C. and K.R. Massarsch (2013). *Soil Heave Due to Pile Driving in Clay*. Sound Geotechnical research to Practice: Honouring Robert D. Holtz II, ASCE. Pp. 481-499.