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Study of The Behavior of Abutment Piled Foundation due to Nearby Staged Embankment (Case Study: Kali Kandang Bridge on The North Ring Road of Lamongan)

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ABSTRACT

Kali Kandang Bridge is built on soft soil with low bearing capacity that uses a combination of Preloading, Prefabricated Vertical Drains (PVD), and Prefabricated Horizontal Drains (PHD) that require a long time to achieve a 90% consolidation degree. During the consolidation process, there is no other work that can be done. To increase time efficiency, shorten the PVD spacing or manage two or more works, such as piling bridge abutment, staged embankment, and consolidation process simultaneously can be done. But, embankment above soft soil near piled foundation can give additional forces to the pile so the study of behavior of abutment piled foundation due to nearby staged embankment and degree of consolidation should be done. This study analyzes the effects to piles if piling is carried out after consolidation is complete. Then, it analyzes the effects of variation of the PVD spacing of 0.75 m and 0.50 m, variations in embankment stages of 0.75 m/day, 1.00 m/day, and 1.25 m/day and variations in piling at various degrees of consolidation ranging from 10% to 90%. From the analysis, it was found that the variation of PVD installation spacing of 0.75 m and 0.5 m and the variation of embankment phasing of 0.75 m/day, 1.00 m/day, and 1.25 m/day did not provide a significant effect on either the soil settlement and consolidation time or the lateral deflection, pile settlement and forces in piles. On the other hand, pile driving at different consolidation degree variations showed a significant effect. The most critical condition where the foundation pile received the largest additional forces was on the foundation pile driven at a consolidation degree of 10%.

Keywords : Pile, Foundation, Staged Embankment, Lateral Deflection, Degree of Consolidation

INTRODUCTION

The construction of the Lamongan North Ring Road Section II with a length of 3,515 km (Sta. 3+250 – 6+764,65) (Figure 1) is part of the Government's programs to avoid 2 (two) double track railway crossings that often cause long vehicle queues. The intersection with the Railway Tracks forms a sharp angle, leading to a frequent accident caused by vehicles slipping on the slippery Railway Tracks. Additionally, the construction of this road aims to divert inter-city traffic and heavy vehicle traffic from the Pantura East Java Road, reducing congestion on the road network within the city of Lamongan.

Figure 1. Location of Kali Kandang Bridge in the North Lamongan Ring Road Construction Project Section II
Source: BBPJN East Java – Bali, 2023

This research was conducted at the Kali Kandang Bridge which is part of the North Lamongan Ring Road Section II project. The bridge is a single-span structure with a length of 45 m. It uses a PCI girder for the upper structure and a pile foundation with a depth of 32 m for the lower structure. The Kali Kandang bridge is built on soft soil with low bearing capacity. The soil improvement method used at this project location, including the oprit area and bridge abutments, involves a combination of Preloading, Prefabricated Vertical Drain (PVD), and Prefabricated Horizontal Drain (PHD) that takes about 4 months from the start of the staged embankment until consolidation is complete. During the consolidation process, other work, including bridge related activities such as piling, cannot be carried out. As a result, the progress curve tends to remain flat during this phase.

To improve time efficiency, it is necessary to accelerate the implementation of work, which can be achieved by speeding up the consolidation process. This can be done by reducing the spacing between PVDs. In their research, Aspar and Fitriani (2016) studied the effect of spacing and PVD installation patterns on soft clay soil improvement. Their findings showed that the triangular configuration pattern provides the most optimal bearing capacity compared to the rectangular pattern. Additionally, the study revealed that reducing the spacing between PVDs allows the planned degree of consolidation to be achieved more quickly.

In addition to accelerating the consolidation time, the embankment phasing speed also affects the settlement and stability of the embankment slope. Mulifandi, Satrya Soemitro and Hardiningsih (2024) conducted a study on the effect of embankment phasing speed on the stability of embankments built on soft soil and soft organic soil. The study used variations in embankment layer thickness of 15 cm, 20 cm, and 25 cm, with consolidation time of 1 day, 3 days, 5 days, 7 days, and 14 days. where the consolidation time was applied every time the embankment height reached 1 m. The results of the study indicated that reducing the thickness of the embankment layer and increasing the consolidation time improved the safety factor, increased settlement, reduced lateral movement, and decreased excess pore water pressure.

On the other hand, construction time efficiency can also be achieved by performing two or more task simultaneously, such as pile driving of the abutment foundation alongside staged embankment and consolidation. However, staged embankment work on soft soil can cause issues, including lateral movement of the piles and additional load on the piles due to consolidation in the soft clay layer (Yakin, Siska, Alawiah, 2017). Furthermore, the presence of an embankment behind the abutment can reduce the overall safety factor of stability, as the embankment increases the load supported by the slope (Rohmawati, Putra, & Nurtjahjaningtyas, 2022).

Therefore, based on this description, it is important to conduct research on the behavior of pile foundation structures affected by staged embankments around them. This is crucial to anticipate potential failures in pile foundations as a result of the proposed time-efficiency measure, which involves constructing abutment foundation piles simultaneously with staged embankments.

LITERATUR REVIEW

Soft Soil

Soft soil is cohesive soil that has a small grain size such as clay and silt. According to Suyono (1984), soft soil generally has the following properties:

1. Small shear resistance;
2. Low permeability;
3. High compressibility is caused by a high void ratio.
4. Has a high water content causing soft soil to have a very low bearing capacity.

According to Bowles (1984), the consistency of cohesive soil can be correlated with the N-SPT value as shown in Table 1.

Table 1. Correlation for Cohesive Parameters

N (blows)	<4	4-6	6-15	16-25	>25
g (kN/m^3)	14-18	16-18	16-18	16-20	>20
qu (kPa)	<25	20-50	30-60	40-200	>100
Consistency	*Very Soft*	*Soft*	*Medium*	*Stiff*	*Hard*

Source: Bowles, 1984

Correction N-SPT Value

For an N value that is below the groundwater level with a kind of sandy soil and an N value larger than 15, the N value must be corrected to N' based on the following equation from Terzaghi and Peck:

$$N' = 15 + 0,5\ (N-15) \quad ... (1)$$

Seed, et al. also present C_N correction factor to correct field N value where:

$$N1 = C_N \cdot N \quad ... (2)$$

and the number of C_N is dependent on the vertical effective soil stress as shown in Table 2.

Table 2. C_N Correction Factor

σ'$_v$	30	50	100	150	200	250	300	350	400	450	500
C_N	1,6	1,22	0,95	0,78	0,65	0,57	0,5	0,45	0,42	0,4	0,39

Source: Seed, et al.

Settlement Analysis in Plaxis

1. **Pile Bearing Capacity**

   Luciano Decourt (1982) provides a method for estimating the bearing capacity of foundation piles based on the NSPT value in the following equation:

$$Q_L = Q_P + Q_S \quad \text{... (3)}$$

$$Q_P = q_P + A_P = (\bar{N}_P \, . \, K) \, . \, A_P \quad \text{... (4)}$$

$$Q_S = q_s . A_s = (\bar{N}_S / 3 + 1) \, . \, A_s \quad \text{... (5)}$$

Where:

- Q_L = Limit bearing capacity (kPa)
- Q_P = Point bearing capacity (kPa)
- Q_S = Friction bearing capacity (kPa)
- $\bar{N}_P$ = Average N-SPT value around 4B above to 4B under pile base (B = foundation diameter)
- K = Soil characteristic coefficient:
  - 12 t/m^2 = 117,7 kPa, for clay
  - 20 t/m^2 = 196 kPa, for clayey silt
  - 25 t/m^2 = 245 kPa, for sandy silt
  - 40 t/m^2 = 392 kPa, for sand
- A_P = Base cross-section area of the pile
- q_P = Stress at the end of the pile
- q_s = Stress due to friction (t/m^2)
- $\bar{N}_S$ = Average N-SPT value along embedded pile ($3 \leq N \leq 50$)
- As = Area of embedded pile cover (m^2)

RESEARCH METHOD

The method used in this research involves finite element numerical simulation with the Plaxis 3D program to analyze settlement and time consolidation of the sub-base, embankment slope stability, lateral deflection and settlement of the piles, and forces in the piles based on variations in PVD spacing, staged embankment, and degree of consolidation during piling. PVD spacing varies between 0.75 m and 0.50 m to accelerate consolidation. The staged embankment is modeled with embankment height increments of 0.75 m/day, 1.00 m/day, and 1.25 m/day. Pile driving is then simulated at varying degrees of consolidation, ranging from 10% to 90%. The data used consists of secondary data obtained from field soil investigations and will be validated using back-analysis methods to determine parameters that align with field conditions based on settlement plate monitoring data.

DATA COLLECTION

Soil Investigation

In this research, soil data used for analysis is secondary data of SPT at BH-11 (Sta. 5+600), BH-12 (Sta. 5+725), BH-13 (Sta. 5+775), and BH-14 (Sta. 5+825) as shown in Figure 2 and laboratory test at BH-12 (Sta. 5+725), as shown in Table 3, around Kali Kandang bridge (Sta 5+739.65).

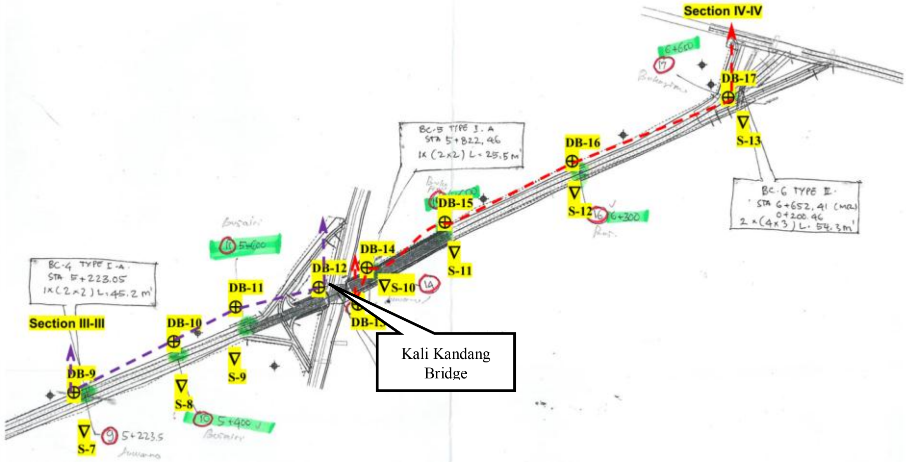

Figure 2. Layout of Soil Investigation
Source: BBPJN East Java – Bali, 2023

Table 3a. Laboratory Test Results

Depth	Soil Type	Soil Classification	Percentage of grains		Physical Properties						
			Sand & Gravel	Clay & Silt	wc	Gs	γ	γd	Sr	e	n
m		USCS	%	%	%	-	kN/m³	kN/m³	%	-	-
2,00 - 2,50	Silty Clay	CH	0,51	99,49	60	2,58	16,10	10,10	99	1,56	0,61
6,00 - 6,50	Silty Clay	CH	0,91	99,09	89	2,53	14,50	7,70	98	2,30	0,70

Source: BBPJN East Java – Bali, 2023

Table 4b. Laboratory Test Results

Depth	Atterberg Limit				Modulus, po condition			Total stress (UU)	
	LL	PL	IP	LI	E_u	E_{oed}	E_{50}^{ref}	c	ϕ
m	%	%	%	%	kN/m²	kN/m²	kN/m²	kN/m²	°
2,00 - 2,50	70	32	38	0,74	8500	3400	3300	27	11
6,00 - 6,50	63	28	35	1,74	4500	1200	2600	10	4

Source: BBPJN East Java – Bali, 2023

Table 5c. Laboratory Test Results

Depth	Kompresibilitas							
	Cc	Cs	λ	κ	Pc'	Po	OCR	Cv
m	-	-	-	-	kN/m²	kN/m²	-	cm²/dt
2,00 - 2,50	0,39	0,09	0,165	0,044	16	34	4,71	5,20E-03
6,00 - 6,50	1,03	0,11	0,325	0,054	8	53	1,51	2,70E-03

Source: BBPJN East Java – Bali, 2023

Soil Monitoring Settlement Plate

The monitoring results that will be used to determine soil parameters for modeling with the Plaxis program are the results of settlement plate monitoring at the Kali Kandang bridge, especially around Abutment 1 (Sta. 5+717), that is SP-53 (Sta. 5+700) as shown in Figure 3.

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The settlement plate is installed at the base elevation of the embankment. The results of the soil monitoring settlement plate can be seen in Figure 4.

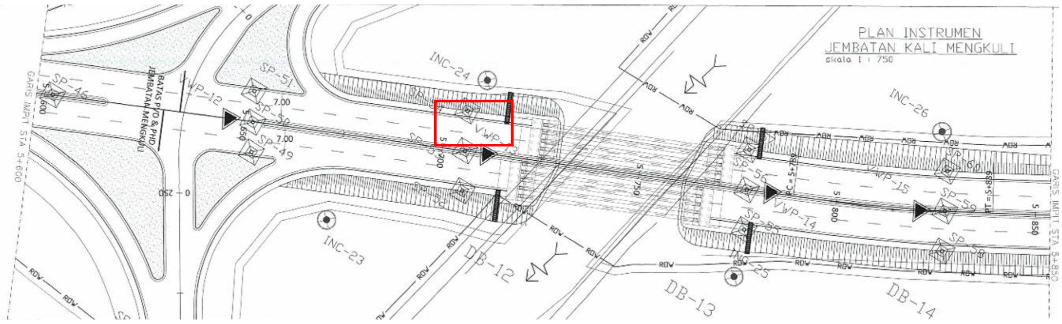

Figure 3. Instrumentation Plan in Kali Kandang Bridge
Source: BBPJN East Java – Bali, 2023

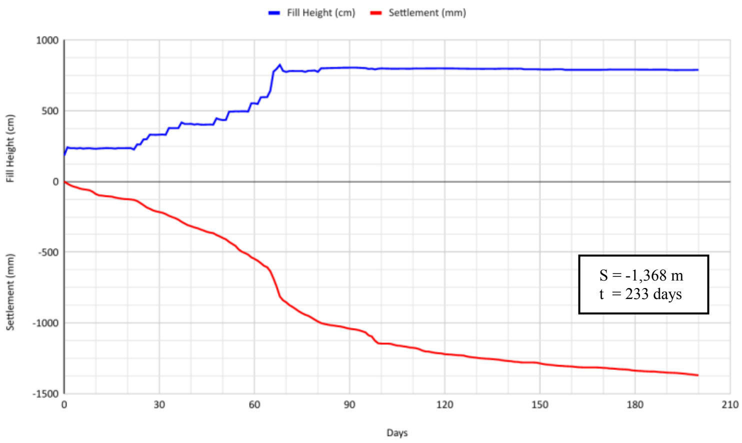

Figure 4. Soil Monitoring Settlement Plate SP-53 Results
Source: BBPJN East Java – Bali, 2024

RESEARCH ANALYSIS

Back Analysis

Back analysis is performed using Plaxis 3D to obtain settlement and consolidation times that closely match the settlement plate results (SP-53), ensuring the model accurately represents actual field conditions. The node observed in the back analysis corresponds to the same point as SP-53, located at Sta. 5+700 CL. The model was created from half of Abutment 1 as shown in Figure 5 and the model in Plaxis shown in Figure 6.

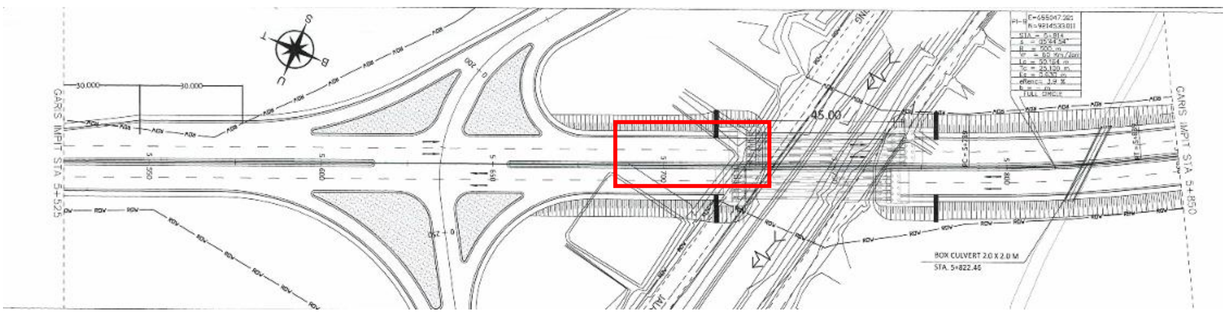

Figure 5. Layout for Modelling in Plaxis 3D

The embankment is planned to have a height of 7.898 m, including a 1.5 m-thick platform embankment designed to accommodate the maximum water level at the project site, which reaches 1.2 m, and to serve as a base for heavy equipment. The soil improvement method used is a combination of preloading and Prefabricated Vertical Drains (PVDs) installed to a depth of 18 m (including the platform embankment), with a triangular configuration and a spacing of 1 m. The model applied in this research is the Mohr-Coulomb model, using a drained condition for the embankment material and an undrained A condition for the sub-base material.

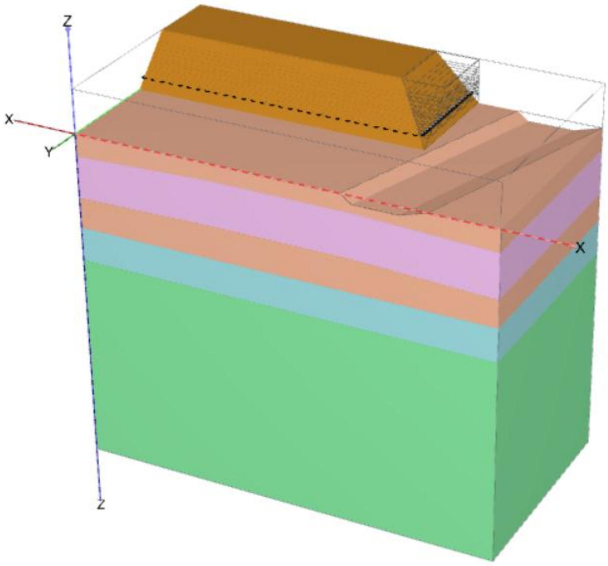

Figure 6. 3D Model in Plaxis

The results of the back analysis are shown in Figure 7, with the input parameter listed in Table 4. The analysis results that the soil settlement for 90% consolidation from the model is -1.381 m, with a consolidation time of 233 days, while the settlement recorded in SP-53 is -1.368 m, with a consolidation time of 226 days. This analysis demonstrates that the back analysis results closely match the field conditions, making the input parameters suitable for use in subsequent modeling.

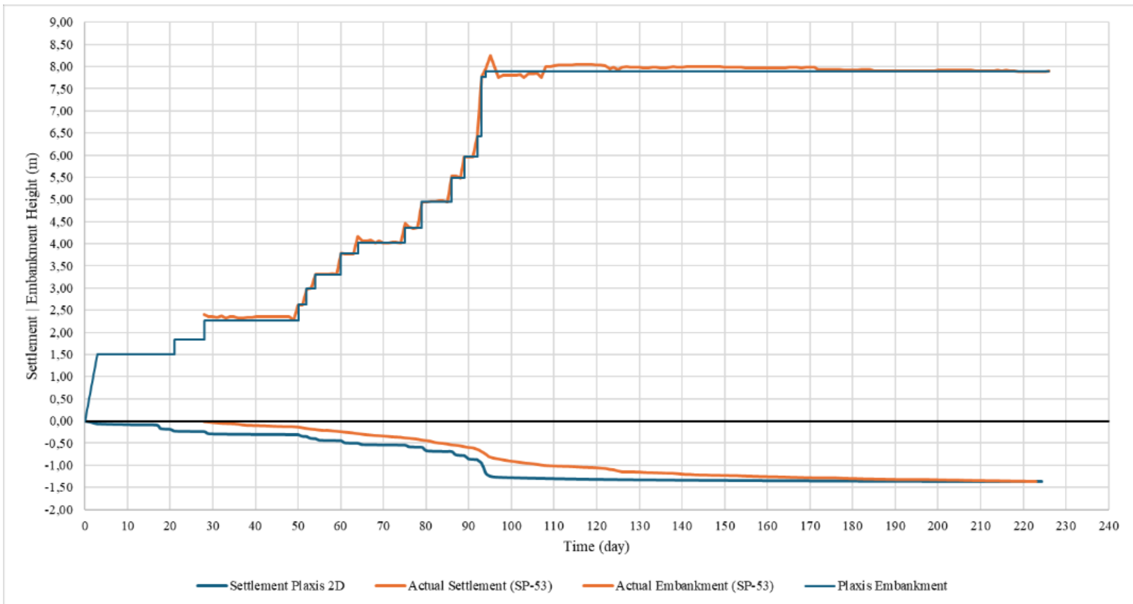

Figure 7. Comparison of Soil Settlement in The Field with Plaxis Modelling Results

Table 6. Parameter Input for Plaxis Modelling

Parameter	Unit	Embankment	Lapis (0-3m dan 11-17m)	Lapis (3-11m)	Lapis (17-23m)	Lapis (23-60m)
		Very Dense	Very Soft	Very Soft	Medium	Stiff
γ_{unsat}	kN/m3	17,86	16,10	14,50	17,26	18,22
γ_{sat}	kN/m3	17,86	16,17	14,64	17,26	18,22
e_0		0,50	1,20	1,70	0,90	0,60
kx	m/day	1,00	4,75E-03	4,75E-03	4,75E-03	4,75E-03
ky	m/day	1,00	4,75E-03	4,75E-03	4,75E-03	4,75E-03
kz	m/day	1,00	4,75E-03	4,75E-03	4,75E-03	4,75E-03
E_{50}^{ref}	kN/m2	20000	2700	2000	6000	10000
c_{ref}	kN/m2	10,00	30,00	23,00	51,00	93,00
ϕ'	deg	35,00	10,00	8,00	25,00	30,00
ψ	deg	5,00	0,00	0,00	0,00	0,00
K_0^{nc}		0,426	0,826	0,861	0,577	0,500

Existing Condition Analysis

Soil settlement and time consolidation under existing conditions are determined from the results of the back analysis. In the existing conditions, piles are driven when consolidation reaches 90% and the preloading embankment has been excavated. However, in this research, pile driving in Plaxis will be simulated without preloading excavation. This research also considers the construction stage where the pile cap has not yet been installed, and the load from the upper structure has not yet been applied. The outputs observed in this model include the lateral deflection and settlement of the piles, as well as the forces acting on the piles.

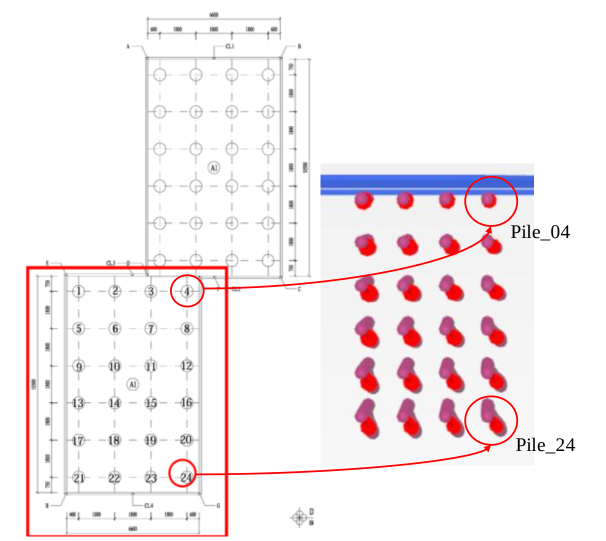

Figure 8. Pile Configuration

The number of piles that will be modelled is 24 piles with the configuration shown in Figure 8 and the pile that will be analyzed is Pile 24 located at the edge and Pile 04 located at the middle. The pile type is a spun pile that has a diameter of 0.6 m with a thickness of 0.1 m and 32 m in length. The bearing capacity of the pile that input in Plaxis was analytically calculated with the equations (3), (4), and (5). The results of this existing condition can be seen in Table 5.

Table 7. Existing Pile Analysis

Pile	Lateral Deflection	Pile Settlement	Nmax	Qmax	Mx	My
	(m)	(m)	(kN)	(kN)	(kN.m)	(kN.m)
Pile 24	0.180	-0.049	-61.816	2.625	4.248	-2.635
Pile 04	0.031	-0.054	-49.382	2.508	1.316	-2.962

Variation Condition Analysis

The variations used in this research are the PVD spacing variations, that is 0.75 m and 0.50 m. While the embankment staging variations are staging 0.75 m/day, 1.00 m/day and 1.25 m/day. The construction stages for each embankment stage are gradual every day until the embankment height of 7.898 m is reached without prior consolidation for each layer of the embankment. Piles are driven at different degrees of consolidation, that is 10% to 90%. After the pile is driven, soil is set until the consolidation degree reaches 90% to obtain movement and internal forces that occur in the pile.

1. Settlement

   The results of the analysis of the influence of PVD spacing and staged embankment can be seen in Figure 9 and Table 6. The analysis results show that staged embankment has a very small and insignificant effect on settlement and on the time required to achieve 90% consolidation.

2. Overall Stability

   As shown in Table 6, the closer the PVD spacing, the higher the safety factor obtained at the maximum embankment height. However, the difference is not significant, and the safety factor value at 90% consolidation is the same across various embankment phasing variations. This is because the range of variations in PVD spacing and staged embankment modeled is relatively small, with only a 25 cm difference, which does not significantly affect settlement, consolidation time, or the safety factor.

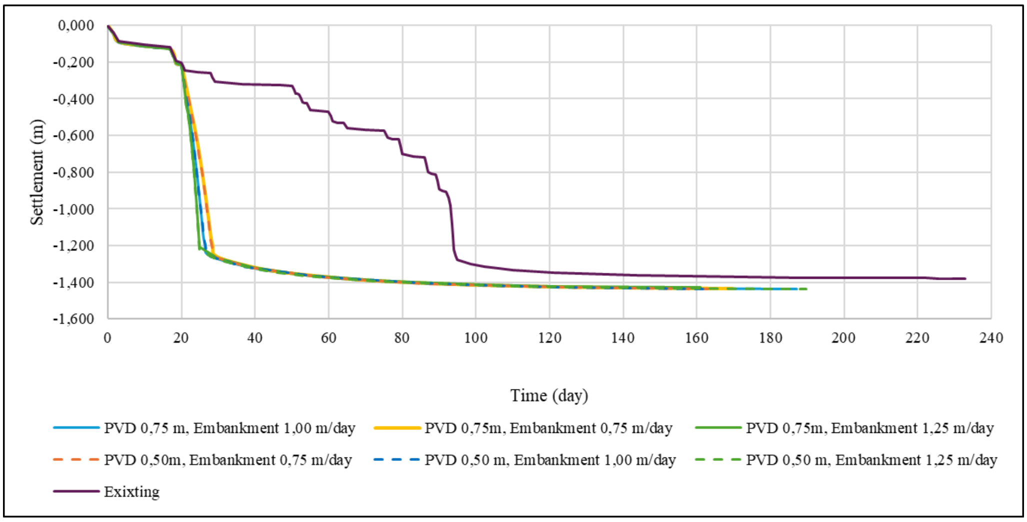

Figure 9. Comparison Settlement in Each Variation

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Table 8. Comparison Settlement, Time, and Stability in Each Variation Before Piling

PVD Spacing (m)	Lift Thicknes s	Staged Embankment (m/day)	Settlemen t (m)	Consolidation Time (day)	SF Top Preload	SF Consolidatio n 90%
0.75	15 cm	0,75	-1.437	170	1.319	1.360
	20 cm	1	-1.436	187	1.317	1.360
	25 cm	1,25	-1.430	161	1.309	1.360
0.50	15 cm	0,75	-1.437	165	1.326	1.361
	20 cm	1	-1.435	163	1.321	1.361
	25 cm	1,25	-1.436	190	1.317	1.361

3. Lateral Deflection

Figure 10 shows the lateral deflection of piles driven at different degrees of consolidation. It is observed that the higher the degree of consolidation during piling, the greater the lateral deflection in the pile. If the pile was driven at a degree of consolidation of 10%, the average lateral deflection would decrease by 1.597% for Pile 24 and by 0.266% for Pile 04 compared to piles driven at a degree of consolidation of 90%. However, this reduction is not significant. Furthermore, Pile 24 experiences greater lateral deflection compared to Pile 04 because Pile 24 is located closer to the embankment slope, resulting in a greater lateral force acting on it.

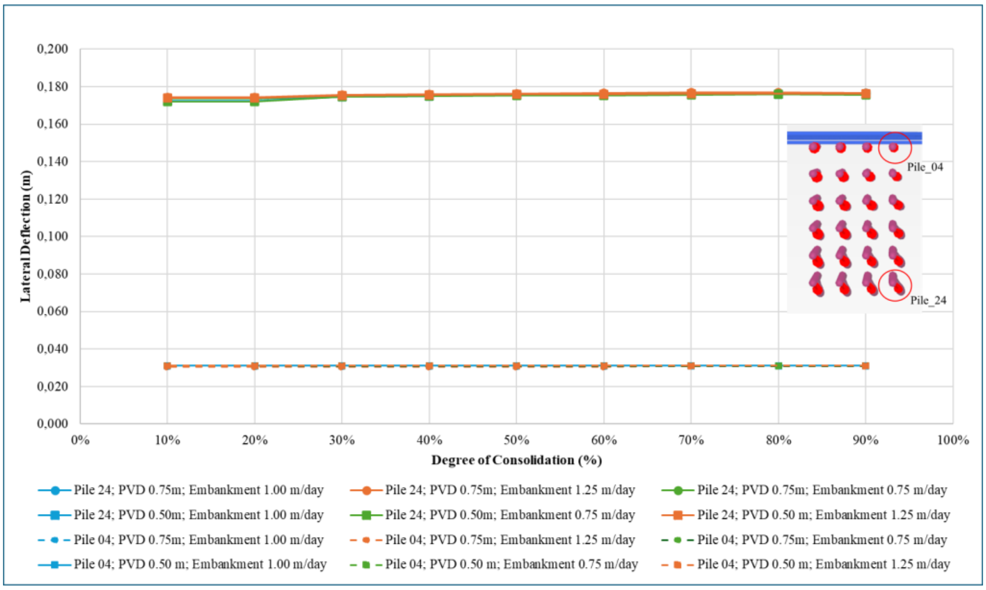

Figure 10. Relationship Between Degree of Consolidation and Lateral Deflection

4. Pile Settlement

Figure 11 shows that the higher the degree of consolidation during pile driving, the smaller the pile settlement. Piles driven at a degree of consolidation of 10% experience an average pile settlement that is 18.45% greater for Pile 24 and 18.02% greater for Pile 04 compared to piles driven at a degree of consolidation of 90%. However, the settlement in Pile 04 is greater than in Pile 24 because Pile 04 is located beneath the center of the embankment, where the maximum settlement occurs.

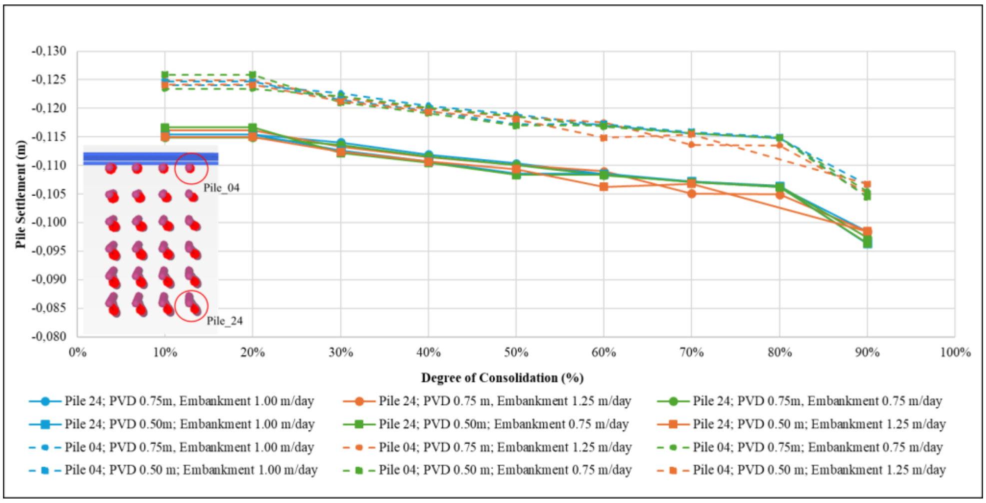

Figure 11. Relationship Between Degree of Consolidation and Pile Settlement

5. Axial Force

Figure 12 explains that piling in different degrees of consolidation has a significant effect on the pile. The higher the degree of consolidation during piling, the smaller the axial force that happened to the pile. Piles driven at a degree of consolidation of 10% experience an average axial force that is 624.13% greater for Pile 24 and 367.84% greater for Pile 04 compared to piles driven at a degree of consolidation of 90%. Furthermore, Pile 24 experiences a greater axial force than Pile 04.

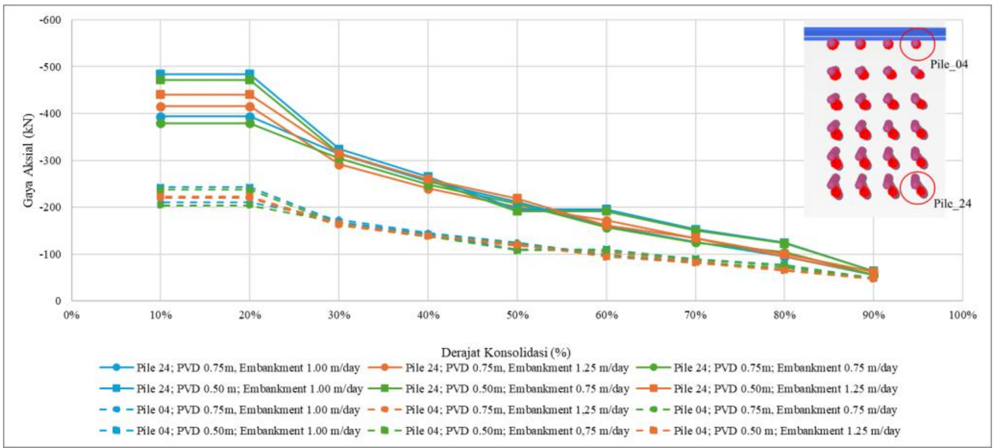

Figure 12. Relationship Between Degree of Consolidation and Axial Force

6. Lateral Force

As well as the influence on the pile's axial force, the degree of consolidation provides similar behavior to the pile when observed from the lateral force. From Figure 13, it can be seen that the higher the degree of consolidation during piling, the smaller the lateral force received by the pile. Piles driven at a degree of consolidation of 10% received an average lateral force 244.38% greater for Pile 24 and 247.70% greater for Pile 04 than piles driven at a degree of consolidation of 90%. And it is shown that a 0.50 m PVD spacing generates more lateral force on the pile than a 0.75 m PVD spacing.

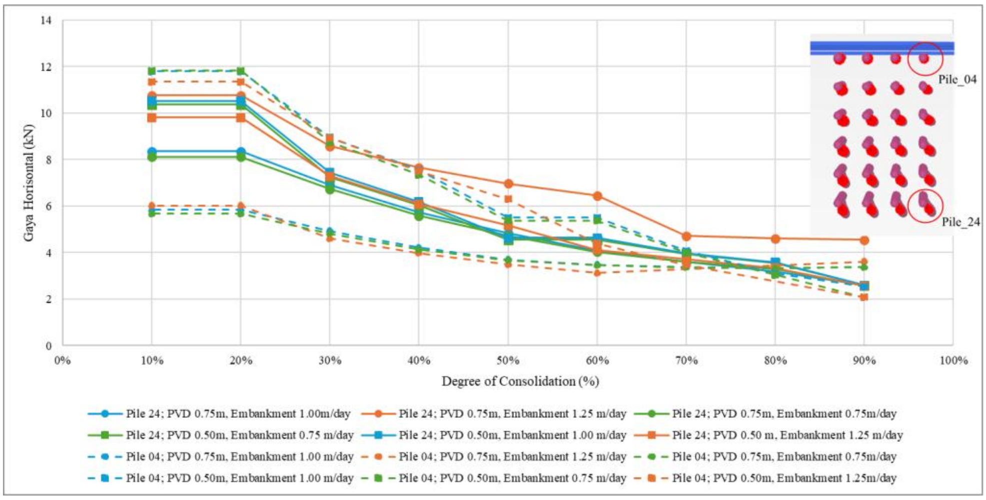

Figure 13. Relationship Between Degree of Consolidation and Lateral Force

7. Moment

Figure 14 and Figure 15 shows the relationship between the degree of consolidation and moment. The higher the degree of consolidation during pile driving, the smaller the moment force experienced by the pile. Piles driven at a degree of consolidation of 10% received an average moment force of 317.39% greater for the x-direction moment and 576.99% greater for the y-direction moment for Pile 24 and 342.38% greater for the x-direction moment and 14.41% greater for the y-direction moment for Pile 04 compared to piles driven at a degree of consolidation of 90%.

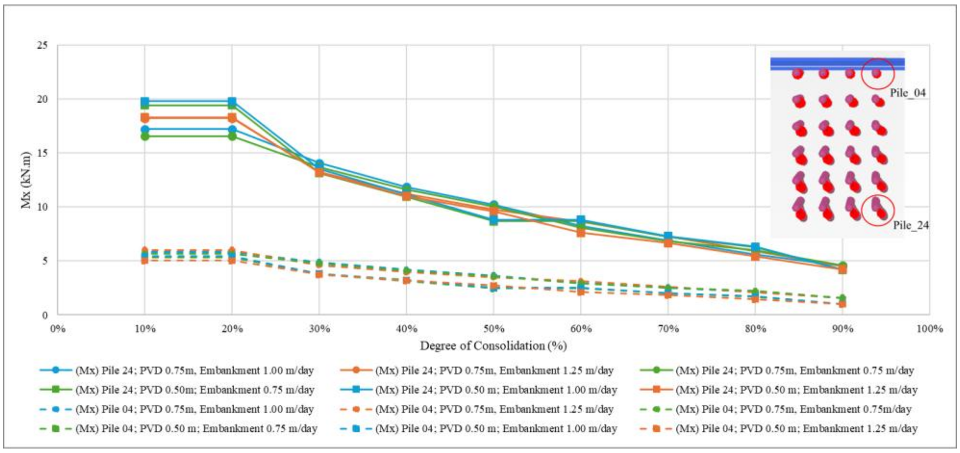

Figure 14. Relationship Between Degree of Consolidation and Moment X Force

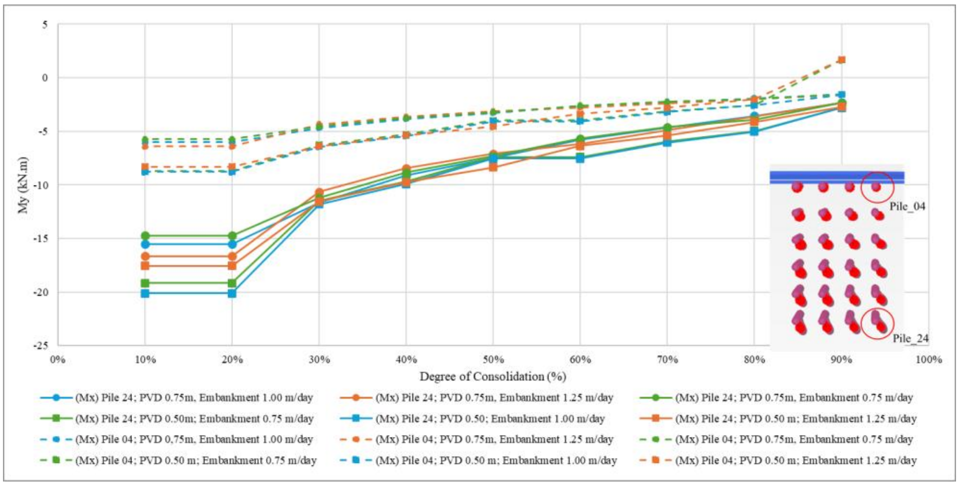

Figure 15. Relationship Between Degree of Consolidation and Moment Y Force

8. Overall Stability

The higher the degree of consolidation during piling, the greater the overall stability safety factor produced (Figure 15). The average increase in SF for 90% consolidation is not significant.

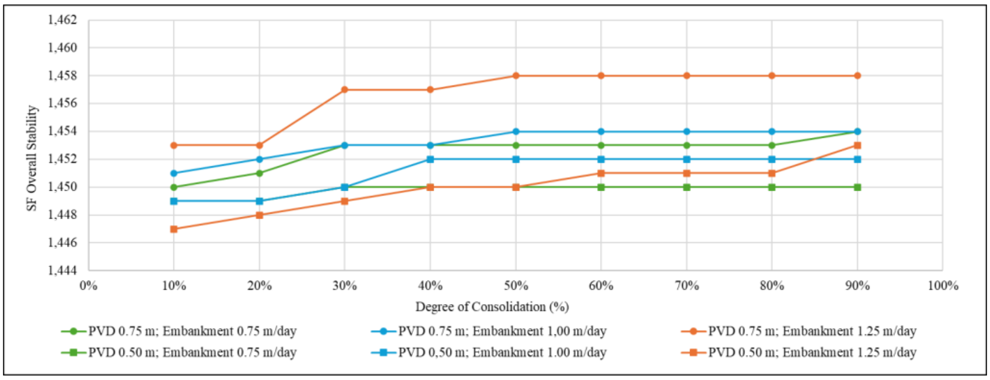

Figure 16. Relationship Between Degree of Consolidation and Pile Settlement

The analysis results that PVD spacing and staged embankment do not significantly affect soil settlement and slope stability. This is likely because the range of variations is too small to produce notable differences in the results. However, the degree of consolidation at the time of pile driving has a significant effect on pile behavior. The earlier the pile is driven, when the degree of consolidation is still low, the greater the additional forces applied to the pile.

CONCLUSIONS

Based on the results of the analysis and calculations in this research, the following points can be concluded:

1. From the back analysis using Plaxis 3D, the settlement that happened in an existing condition with height of 7.898 m embankment is -1.381 m in 233 days.
2. The results of the analysis of existing conditions are:
   a. The lateral deflection that occurs is 0.180 m for Pile 24 and 0.031 for Pile 04,
   b. The pile settlement that occurs is 0.049 m for Pile 24 and 0.054 for Pile 04,
   c. The axial force that occurs is 61.816 kN for Pile 24 and 49.382 for Pile 04,
   d. The lateral force that occurs is 2.625 kN for Pile 24 and 2.508 for Pile 04,

   e. The moments in the x and y directions are 4.212 kN.m and -2.635 kN.m for Pile 24, and 1.316 kN.m and -2.962 kN.m for Pile 04.
3. Variations in the PVD installation spacing of 0.75 m and 0.5 m and variations in the embankment phasing of 0.75 m/day; 1.00 m/day and 1.25 m/day do not provide a significant effect on either settlement and consolidation time. Also, the influences on lateral deflection, pile settlement, and internal forces that occur in the pile are not significant.
4. On the other hand, piling at different degrees of consolidation had a significant effect. Pile 24, driven at a 10% degree of consolidation, resulted in an 18.45% increase in average pile settlement, a 624.13% increase in average axial force, a 244.38% increase in average lateral force, and increases in average moment forces in the x and y directions of 317.39% and 576.99%, respectively. Similarly, Pile 04, driven at a 10% degree of consolidation, resulted in an 18.02% increase in average pile settlement, a 367.84% increase in average axial force, a 247.70% increase in average lateral force, and increases in average moment forces in the x and y directions of 342.38% and 14.41%, respectively.

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