

## Response of Existing Foundation to Underground Channel Tunneling Activities

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### ABSTRACT

The construction of underground channels beneath existing infrastructure, particularly elevated bridges, poses significant risks to structural stability. This research investigates the impact of slurry machines on existing pile foundations through 3D numerical modeling using MIDAS GTS NX. The analysis focuses on variations in Total Thrust Force (F) and conduit depth, considering two Total Thrust Force (F) scenarios and two conduit positions (0.5Doc and 1.5Doc below the pile tip). The results demonstrate that Total Thrust Force is a critical factor influencing the structural response of existing foundation to underground channel tunneling activities, where increased Total Thrust Force (F) leads to higher deflection, settlement, and bending moment. Additionally, deeper conduit positioning mitigates these effects, indicating that conduit depth plays a significant role in reducing structural impact. The maximum bending moment is observed at the pile head, suggesting that this area requires special attention for structural reinforcement. Furthermore, the absence of tie beams in a statically indeterminate structure amplifies the effect of foundation movements on the superstructure. This research provides valuable insights for planning safe underground conduit construction beneath existing bridge structures and highlights the importance of optimizing tunneling parameters to minimize structural risk.

**Keywords:** Adjacent conduit; tunneling; underground channel; response group pile; hardening soil; Midas GTS NX.

### INTRODUCTION

The construction of underground channels (conduits) in crowded areas, such as South Jakarta, has the potential to disrupt traffic, daily community activities, and existing infrastructure. If the conduit is built beneath the foundation of an existing elevated bridge, it may affect the bridge's stability and safety, making it essential to assess the potential impacts.

Tunneling parameters such as Thrust Force (TF) and Cutterhead Torque (T) are significantly influenced by geological conditions (Hu et al., 2023; Qiao et al., 2023; Yan, 2022a, 2022b; Yan et al., 2023). Therefore, experienced tunneling machine operators must continuously monitor these parameters and make appropriate decisions based on ground conditions. Among these parameters, the Total Thrust Force (F) in slurry machines plays a crucial role in maintaining the stability of the tunneling face. This force can be directly controlled by the operator through a system of hydraulic cylinders (Wang, Gong, Shi, & Yang,

2012). If the TF drops too low, the cutting face may collapse, leading to ground settlement. Conversely, excessive TF may induce ground heave. Thus, rational control of TF is essential to ensure the safety of tunneling operations using slurry machines. A previous study proposed an empirical formula,  $F = \beta D^2$  (where  $D$  is the diameter of the shield machine, and  $\beta$  is an empirical coefficient related to geological conditions). The value of  $F$  is determined based on the conduit diameter and coefficient  $\beta$ , which is applied within a range between the lower boundary of 500 and the upper boundary of 1200 (Xie et al., 2024).

In addition, the depth of the underground channel can significantly influence the stability of existing foundation structures, particularly those of elevated bridges. Therefore, variations in channel depth, as examined in this study, represent a critical factor that must be carefully considered during construction planning.

Previous studies have shown that the presence of tunnels near pile foundations can lead to several adverse effects, such as settlement of the pile foundations, increased axial loads, and induced bending moments along the pile shafts (S. Ma et al., 2017; S. K. Ma et al., 2015; Mangi et al., 2020; Soomro et al., 2017, 2023). These conditions are clearly unfavorable for the performance and safety of pile foundations. In addition, research by Soomro et al. (2017) indicates that greater tunnel depth is generally associated with reduced settlement in pile foundations, exhibiting a consistent trend. This observation aligns with the findings of Wang, Yan, Wang, and Li (2024), who reported that the maximum horizontal displacement of piles occurs at the depth corresponding to the tunnel alignment.

This research aims to analyze the impact of tunneling activities using slurry machines on the stability of existing bridge foundations, focusing on variations in Total Thrust Force ( $F$ ) and conduit depth. The goal is to provide a better understanding of how these parameters affect the deflection, settlement, and bending moments of the pile foundation, as well as to identify effective mitigation measures. The benefits of this study include serving as a guide for planning the construction of safe underground tunnels in infrastructure-dense areas, reducing the risk of damage to existing structures, and providing practical recommendations for optimizing tunneling parameters to ensure the stability of the foundation and overall structural safety.

## METHOD

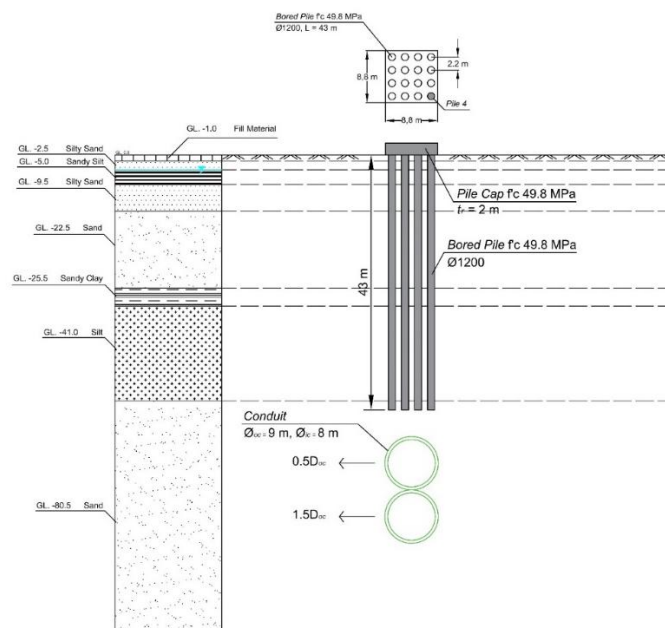
Based on the results of the Standard Penetration Test (SPT), the soil considered in this site is predominantly silty sand and fine to very fine sand, with the groundwater table located at a depth of 2,5 m below the surface. The tunneling process using a slurry machine is planned at depths ranging from 47,5 to 61 m, passing through fine to very fine sandy layers characterized by low plasticity and classified as dense soil. Table 1 presents the soil properties used as input parameters in the numerical analysis.

**Table 1. Soil Strength Parameters for the Hardening Soil Model**

Depth (m)	Soil Description	N- SPT	Soil Type	$\gamma_{sat}$ kN/m <sup>3</sup>	$\gamma_{unsat}$ kN/m <sup>3</sup>	$c'$ (kN/m <sup>2</sup> )	$\phi'$ (°)	$E_{50}^{ref}$ (kN/m <sup>2</sup> )	$E_{cod}^{ref}$ (kN/m <sup>2</sup> )	$E_{ur}^{ref}$ (kN/m <sup>2</sup> )
0,0 – 1,0	Fill Material	-	CH	17	16	5	20	15.000	10.500	45.000
1,0 – 2,5	Silty Sand	-	SC	18	17	5	26	20.000	14.000	60.000
2,5 – 5,0	Sandy Silt	13	MH	16	15	5	17	25.000	17.500	75.000
5,0 – 9,5	Silty Sand	21	SC	19	18	6	28	30.000	21.000	90.000
9,5 – 22,5	Sand	30	SW	20	19	5	32	50.000	35.000	150.000
22,5 – 25,5	Sandy Clay	26	CH	16	15	6	29	40.000	28.000	120.000
25,5 – 41,0	Silt	40	MH	17	16	7	30	50.000	35.000	150.000
41,0 – 49,0	Sand	42	SW	21	20	5	33	52.000	36.400	156.000

Note:  $E_{cod}^{ref} = 0,7 E_{50}^{ref}$ ;  $E_{ur}^{ref} = 3E_{50}^{ref}$

Source: SPT data analysis and ground model calibration using MIDAS GTS NX, 2024



**Figure 1. Soil Profile Used for The Analysis**

Source: Geotechnical modeling results based on drill data and laboratory tests, 2024

The underground channel (conduit) will be installed beneath the existing bridge foundation has an outer diameter of 9 m and an inner diameter of 8 m. The foundation consists of a pile cap with dimensions of 8,8 m × 8,8 m and a thickness of 2 m. The pile cap is connected to 16 bored piles arranged in a 4×4 configuration. Each bored pile has a length of 43 m and a diameter of 1,2 m.

The conduit is assumed to be located at depths of 4,5 m below the pile tip (0.5Doc) and 13,5 m below the pile tip (1.5Doc). The conduit positions are illustrated in the Figure 1. The is assumed to extend 36 m in length, using a shield machine with a length of 3 m and segmental lining with a length of 1,5 m each.

The tunneling process involves three main types of materials. First, segmental linings made of precast concrete with a unit weight of 24 kN/m<sup>3</sup>. Second, the shield machine, which functions as the tunneling equipment and is made of steel with a unit weight of 78 kN/m<sup>3</sup>. Third, grouting, which is used to fill the gaps and bond the segmental linings together, with a unit weight of 22 kN/m<sup>3</sup> (see Table 2).

In this study, a total of 24 segmental linings are used, each with a length of 1,5 m (the detailed specifications of the conduit can be seen in the Table 3). For every tunneling cycle performed by the shield machine with length 3 m, two segmental linings are installed sequentially (see Figure 2).

**Table 2. Properties of Conduit**

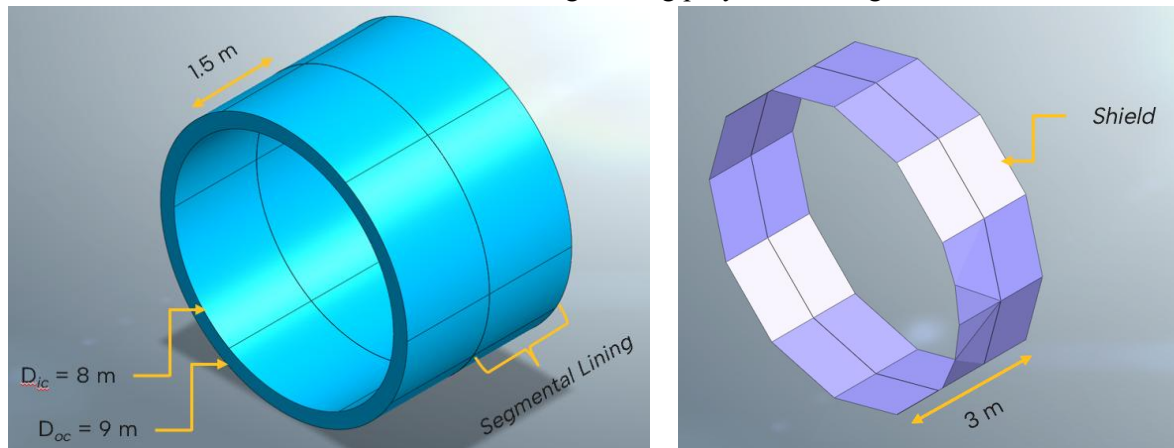
Material	Unit Weight	Modulus of Elasticity
	kN/m <sup>3</sup>	GPA
Steel	78	250
Precast concrete	24	28,7
Grouting	22	10,0

Source: Technical specifications of the manufacturer of materials and literature related to tunneling, 2024

**Table 3. Conduit Specification**

Conduit Specification	Description
Outer diameter	9 meter
Inner diameter	8 meter
Shield material	Steel
Segmental lining material	precast concrete
Conduit length	36 meter
Segmental lining length	1,5 meter
Number of segmental lining	24
Grouting Material	Concrete

Source: Dokumen desain engineering proyek tunneling, 2024

**Figure 2. Detail of Conduit**

Source: Tunneling project engineering design document, 2024

The loading during tunneling consists of four types of loads: Thrust Force (TF), Drilling Pressure (DP), Shield External Pressure (SP), and External Segmental Pressure (EP). The values of TF and DP are influenced by the Total Thrust Force (F). In this study, the response of the existing bridge foundation to tunneling activities is analyzed by comparing two levels of Total Thrust Force: F1, equal to 60.000 kN representing the lower boundary, and F2, equal to 95.000 kN representing the upper boundary. This analysis aims to provide insights into the influence of varying F on the stability of the existing bridge foundation at four different underground channel depths. Understanding this relationship is essential to evaluate the impact of load variations during tunneling and to determine appropriate mitigation measures to ensure the overall stability of the existing foundation.

The numerical analysis in this study was conducted using MIDAS GTS NX 3D software, with a soil model geometry of 60 m × 36 m × 111 m. The Hardening Soil (HS) model was applied to represent the soil behavior. In this model, the soil was meshed using Hexa Mesh (hybrid mesher), with a mesh size of 1 m in the first soil layer and 4 m in the following layers. Meanwhile, the mesh for the tunneling area was also generated using Hexa Mesh (hybrid mesher) with a mesh size of 1 m.

The pile cap was modeled using shell elements with concrete properties corresponding to a compressive strength of  $f'_c$  49.8 MPa. Meanwhile, the bored pile was represented using three different element types. The first is a beam element, which simulates the elastic behavior of the pile using concrete with a compressive strength of  $f'_c$  49.8 MPa. The second is a pile

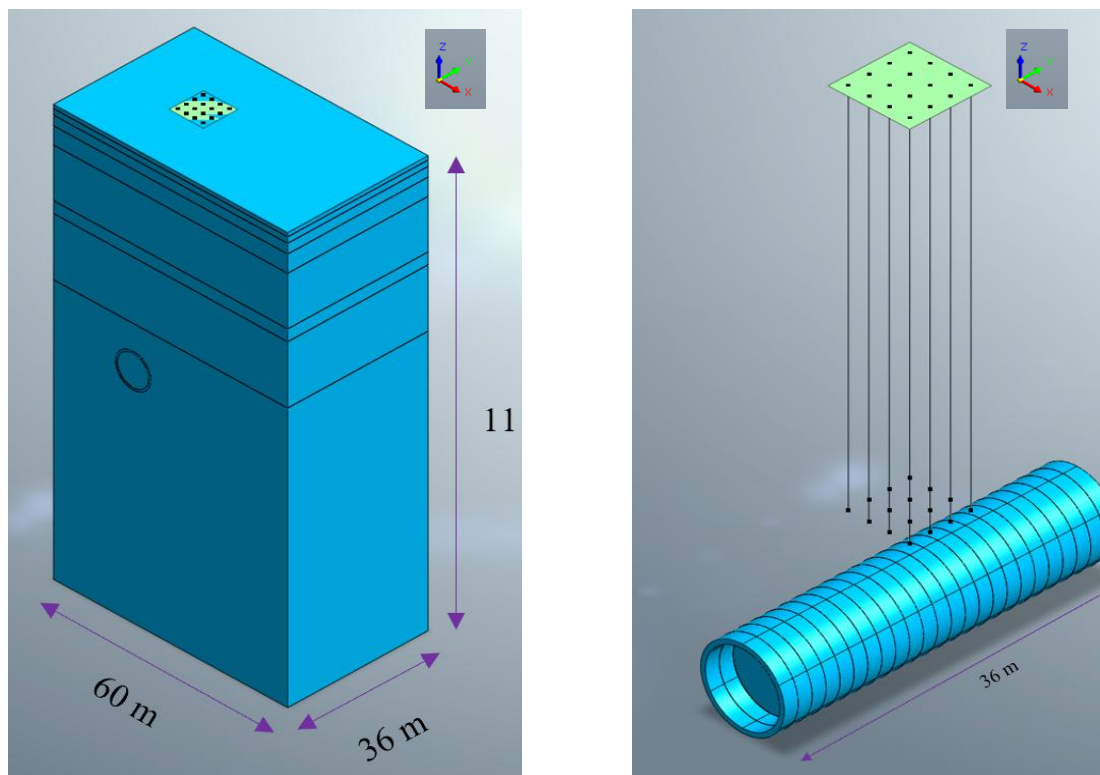
interface element, used to model the allowable shear force along the pile shaft. The third is a pile tip element, which represents the allowable end bearing resistance at the pile base.

In this study, the pile cap is assumed to be rigid and non-interacting with the ground. Consequently, all loads are directly transferred to the piles without any additional support from the soil.

The bored pile is assumed to have a fixed-head condition, as the pile head is directly connected to the pile cap. To represent this condition, a constraint is applied at the pile head with a no-rotation but free to translate.

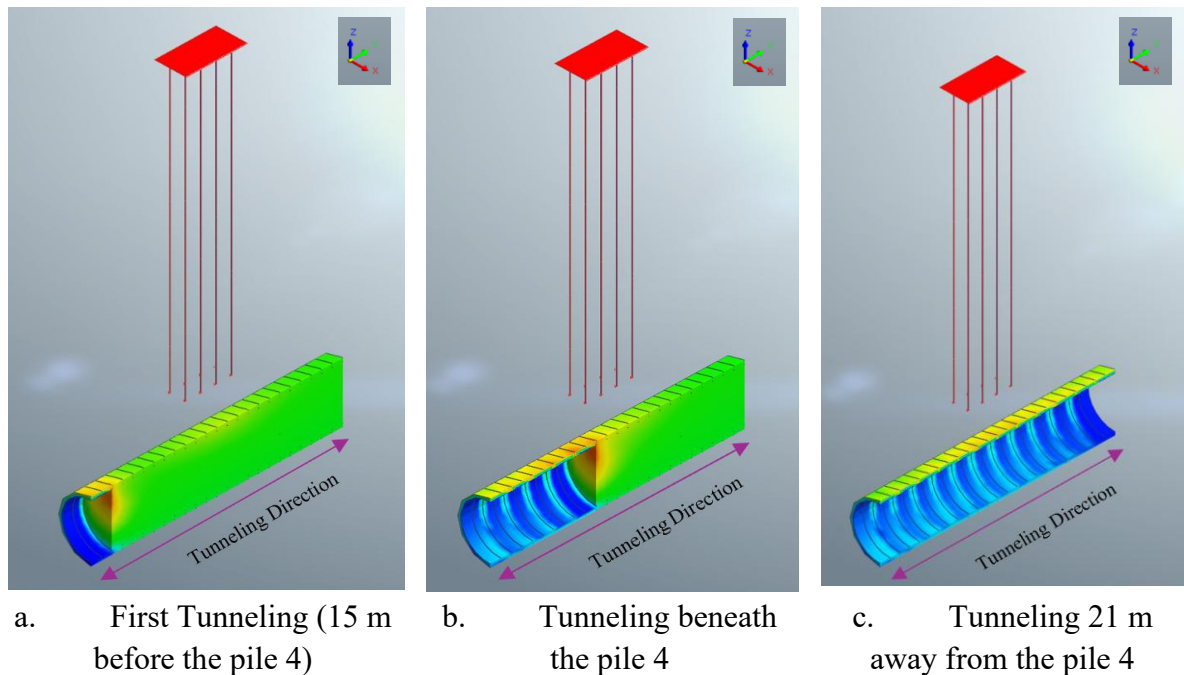
During the analysis stage, calculations were performed using a non-linear soil analysis approach. According to (Basile, 2014), Use of a non-linear soil model is of basic importance in the design, as it enables the avoidance of the exaggeration of stress at the pile group corners (a common limitation of purely linear models), thereby reducing consequent high loads and moments.

The analysis results obtained from Midas GTS NX in this study focus on the bending moment in the direction of tunneling, specifically the Y-axis (bending moment Y). For deflection, the value considered is the movement of Pile 4 in the same direction as the tunneling, represented by translation along the Y-axis (TY translation).



**Figure 3. Geometry in Midas GTS NX**

Source: 3D modeling results with MIDAS GTS NX software version 3.1, 2024



**Figure 4. Tunneling Illustration**

Source: Simulation of the construction stages in the MIDAS GTS NX, 2024

## RESULT AND DISCUSSION

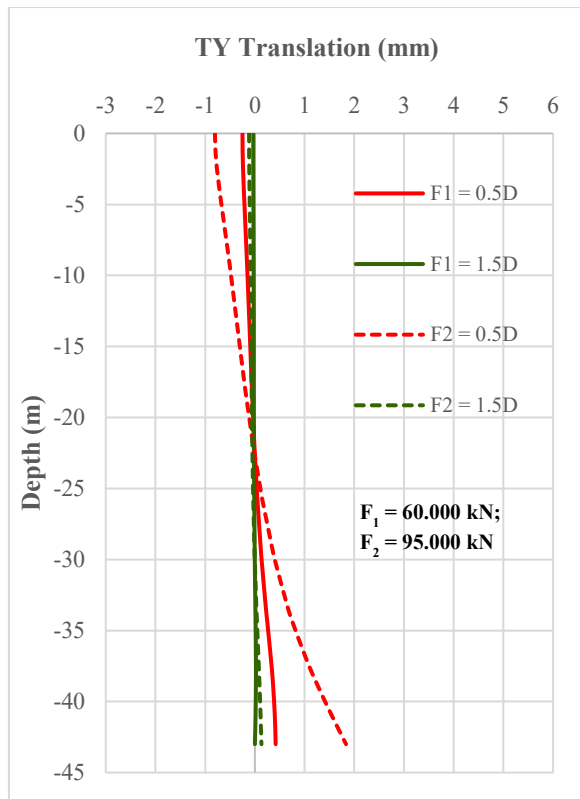
### Pile Deflection

The maximum deflection of the existing pile foundation due to tunneling activity occurs at the pile tip. Additionally, a difference in deflection direction between the pile head and pile tip is observed, indicating the structural response of the existing pile foundation to external forces induced by the tunneling. At the pile head, the deflection is negative, meaning it occurs in the opposite direction of the slurry machine movement. In contrast, the deflection at the pile tip is positive, aligning with the direction of the slurry machine movement (see Figure 5).

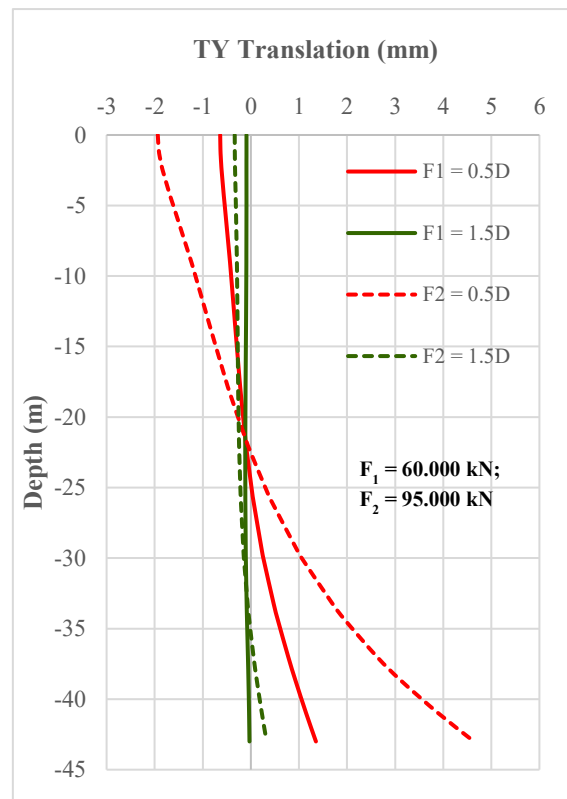
The movement of the slurry machine also affects the amount of deflection in the existing pile foundation. The closer position of the slurry machine to the foundation, the greater the deflection that occurs. However, the 0.5Doc condition, a reduction in deflection began to occur as the slurry machine moved 15 m away from the foundation (see Figure 6 and Figure 7), indicating a weakening effect on the influence of the existing pile foundation structure at that distance.

The Total Thrust Force (F) has a significant influence on the deflection of the existing pile foundation. The greater the total thrust force value, the resulting pile deflection also becomes larger. Additionally, the depth of tunneling affects the deflection rate: the deeper the conduit is located, the smaller the pile deflection tends to be. This trend is illustrated in Figure 6 and Figure 7. At a conduit depth of 0.5Doc, upper boundary Total Thrust Force (F2) results in significantly greater deflection compared to the condition with lower boundary Total Thrust Force (F1). Therefore, the conduit depth plays a role in reducing the effect of force on pile deflection.

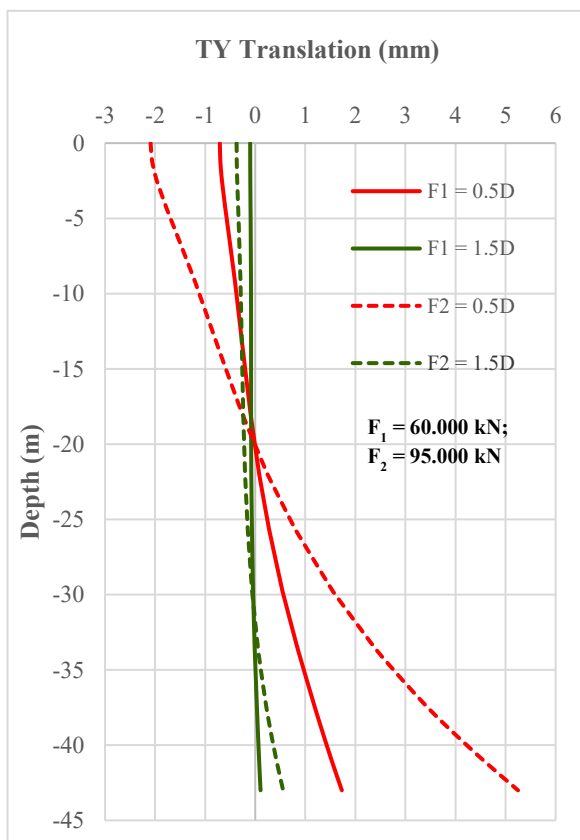
# Response of Existing Foundation to Underground Channel Tunneling Activities



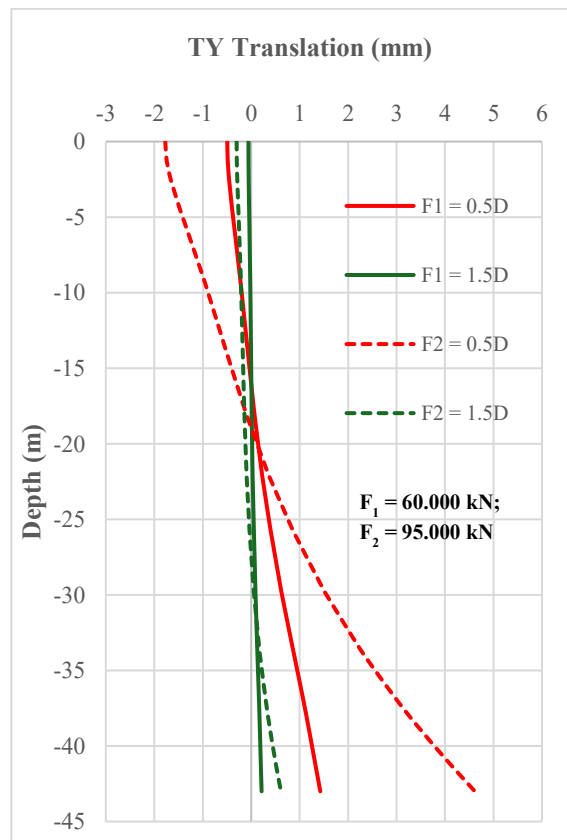
a. First Tunneling (15 m Before the Pile 4)



b. Tunneling Beneath the Pile 4

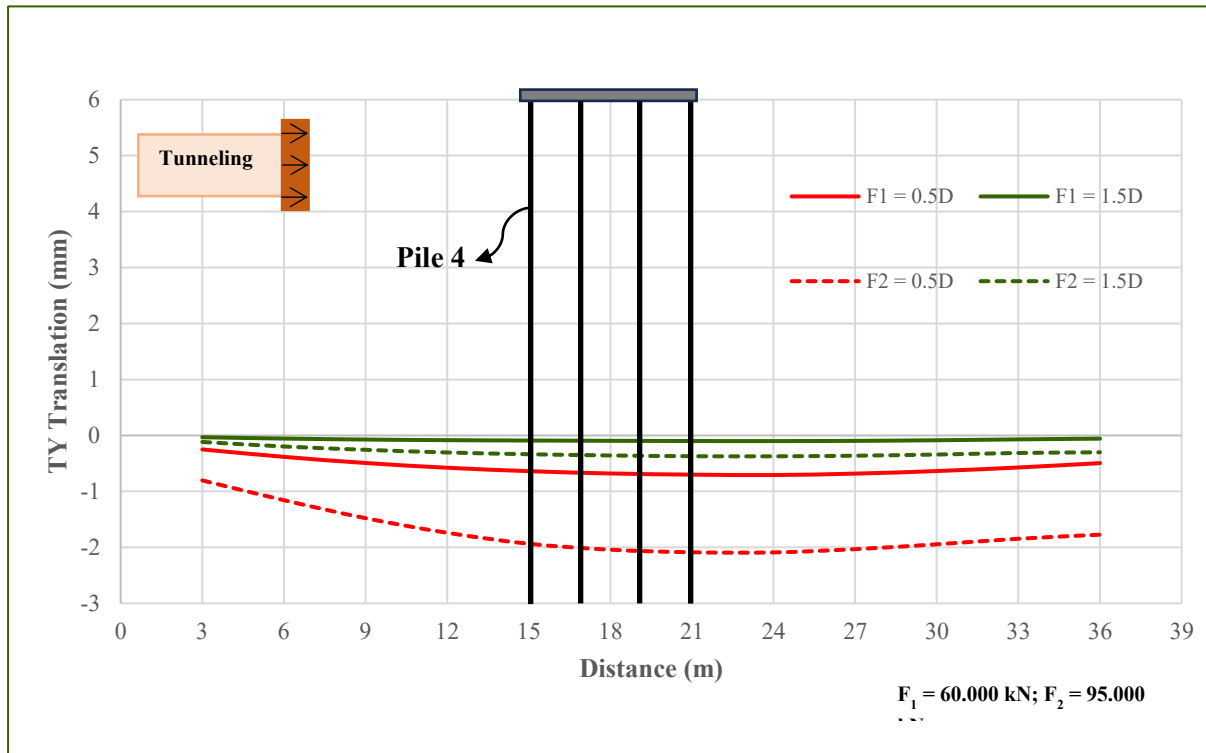


c. Tunneling 9 m Away from the Pile 4



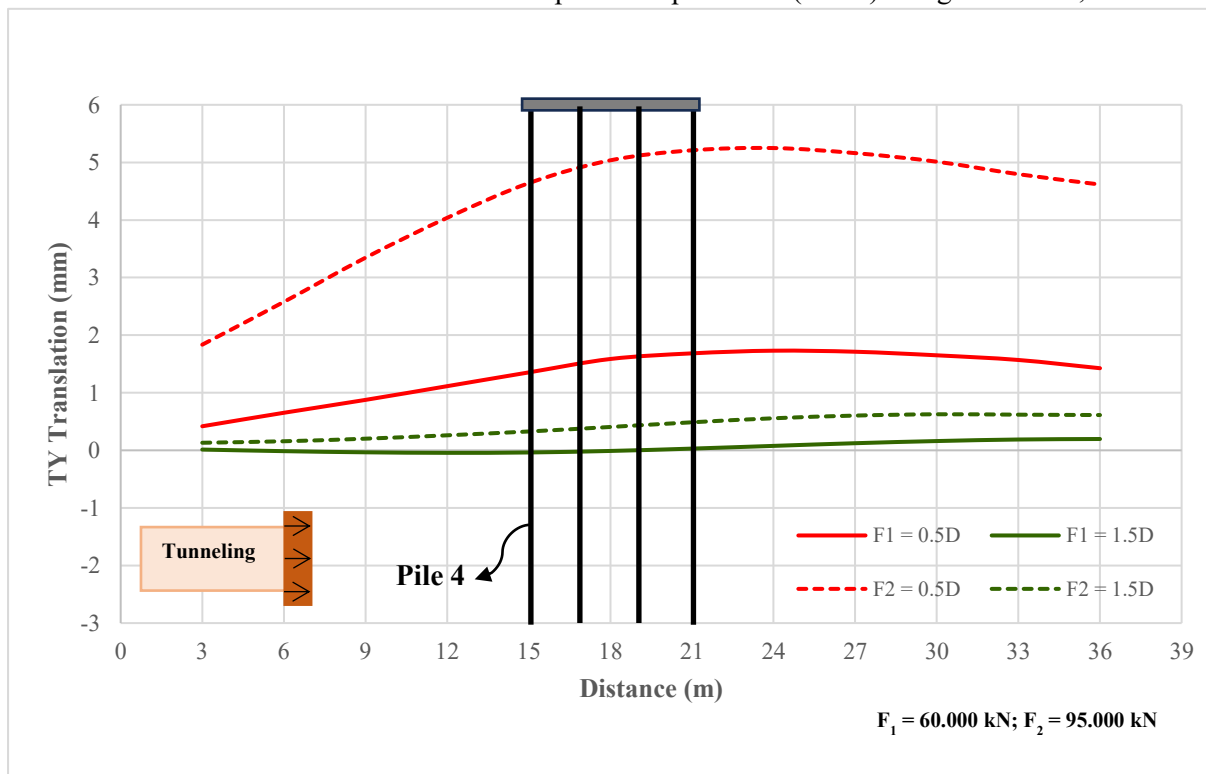
d. Tunneling 21 m Away from the Pile 4

**Figure 5. Deflection Due to Variations in Total Thrust Force (F)**



**Figure 6. Deflection at Pile Head**

Source: Lateral movement simulation output at the pole head (Pile 4) along the Y axis, 2024



**Figure 7. Deflection at Pile Tip**

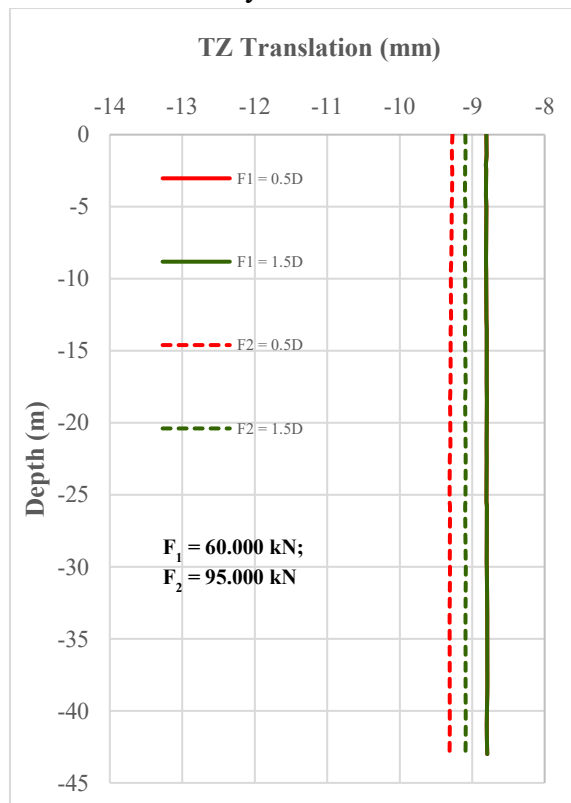
Source: Output of simulated lateral movement at the end of the pole (depth of 43m) along the Y-axis, 2024

**Pile Settlement**

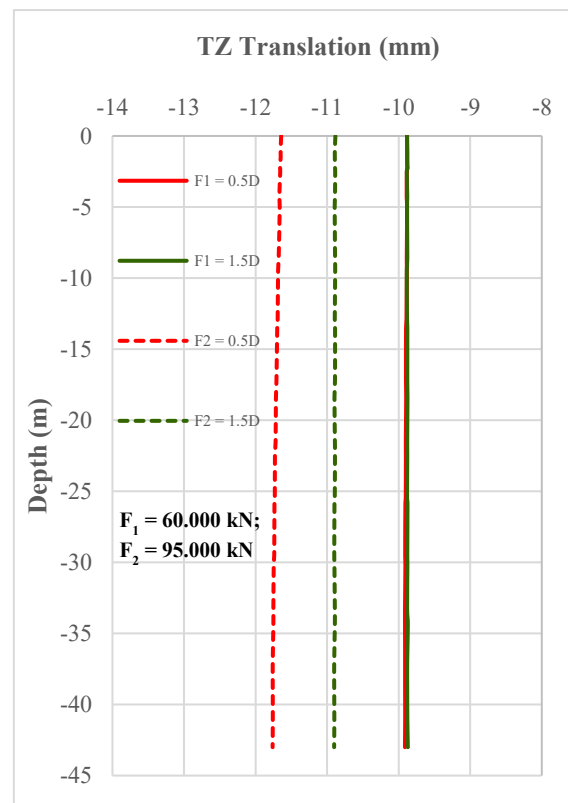
Based on Figure 8, the settlement along the shaft of the existing pile foundation is relatively uniform. Meanwhile, Figure 9 shows that lower boundary Total Thrust Force (F1), the depth of the conduit has no significant impact on the foundation settlement. However, when the Total Thrust Force is relatively upper boundary (F2), conduit depth begins to influence the magnitude of settlement. This indicates that the key factor affecting the extent of settlement is the value of the Total Thrust Force (F) applied during the tunneling process. The greater the total thrust force, the greater the resulting settlement in the existing pile foundation.

In the early phase of tunneling, immediate settlement was observed, ranging from 8.80 mm to 9.09 mm. The subsequent settlement rate decreased significantly after this stage.

The settlement of the existing pile foundation tends to continue during the tunneling process. However, at 0.5Doc condition, after the tunneling beyond 18 m from the existing pile foundation, the rate of settlement begins to decrease (see Figure 9). This phenomenon is attributed to the fact that the external pressure induced by the tunneling is no longer concentrated directly beneath the foundation.

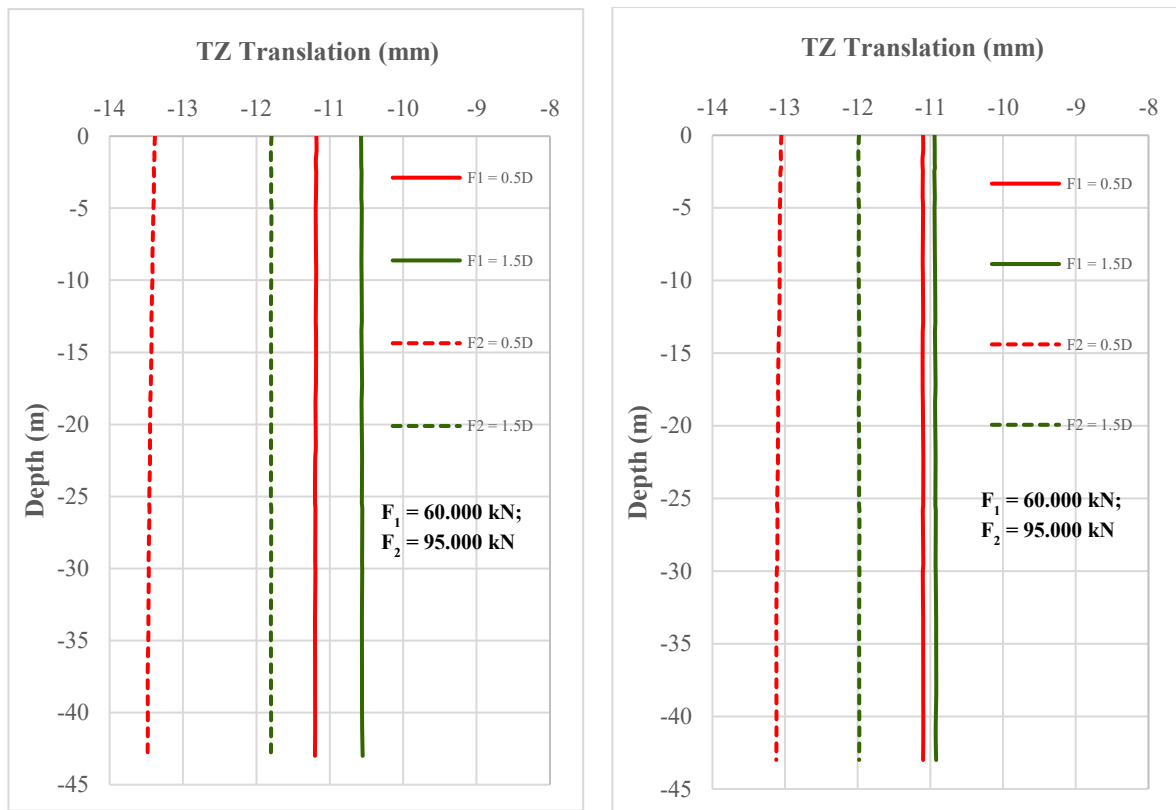


a. First Tunneling (15 m Before the Pile 4)



b. Tunneling Beneath the Pile 4

# Response of Existing Foundation to Underground Channel Tunneling Activities

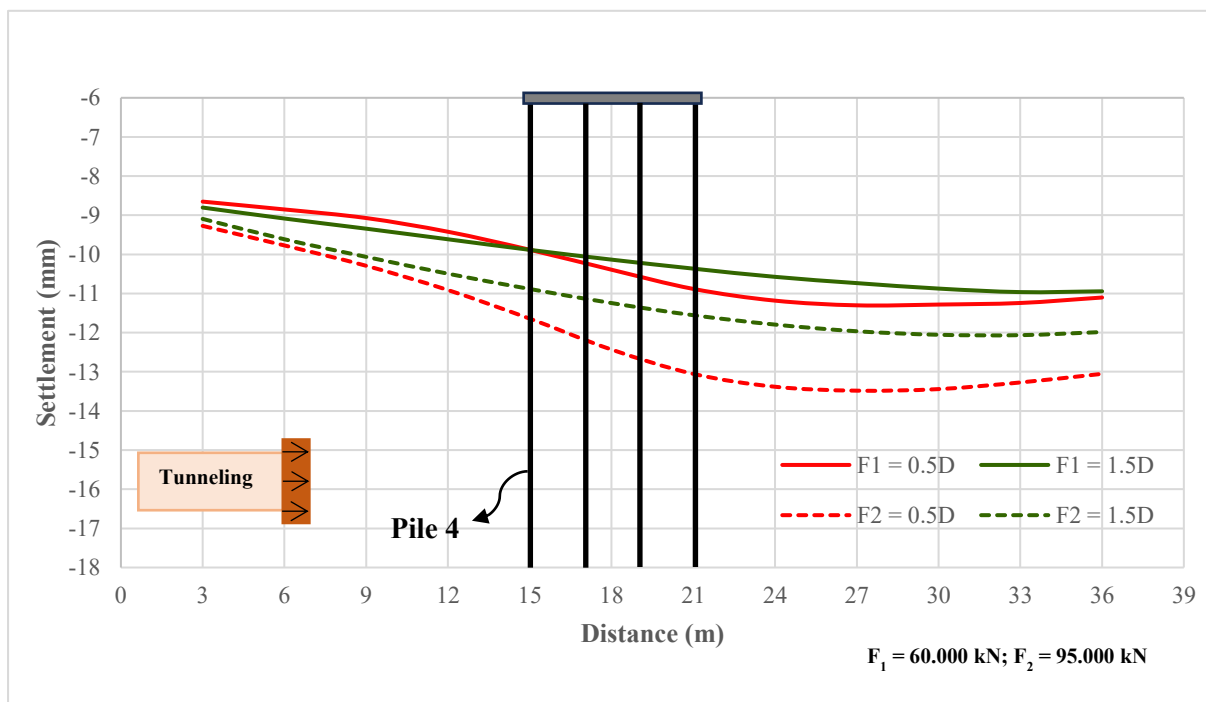


c. Tunneling 9 m Away from the Pile 4

d. Tunneling 21 m Away from the Pile 4

**Figure 8. Settlement Due to Variations in Total Thrust Force (F)**

Source: Results of vertical settlement simulation with thrust force variation, 2024



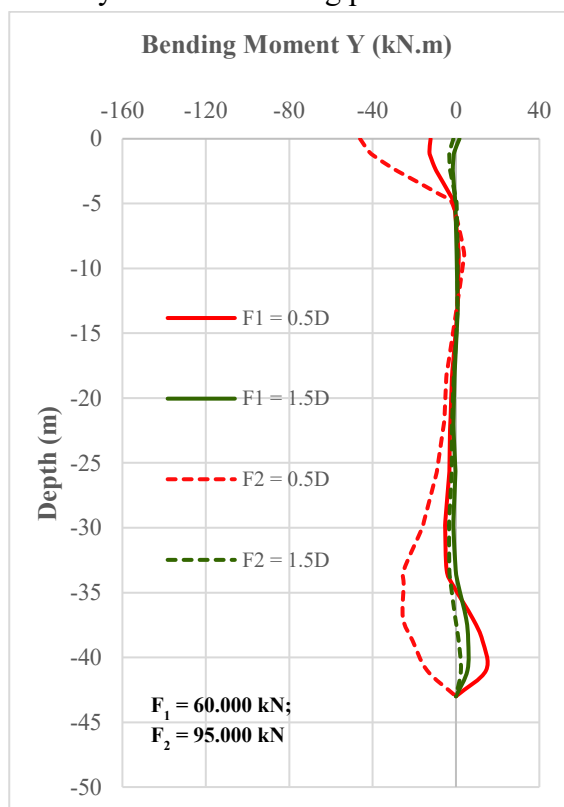
**Figure 9. Settlement of Pile**

Source: Cumulative settlement data along the shaft pile from non-linear simulations, 2024

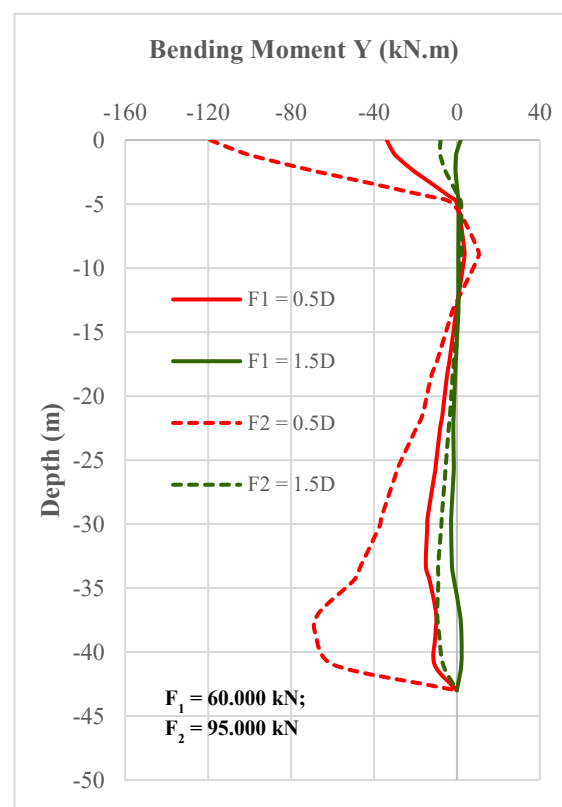
### Pile Bending Moment

The variation in bending moment due to different magnitude of Total Thrust Force (F) is clearly observed at the pile head and at a depth of 34 m until 43 m, with the maximum bending moment occurring at the pile head. As the Total Thrust Force (F) increases, the resulting bending moment also increases, with the moment direction at the pile head tending toward the negative (see Figure 10). This indicates that the induced bending moment acts in the opposite direction to the movement of the slurry machine. In addition to the influence of Total Thrust Force (F), the depth of the conduit also plays a role in the magnitude of the bending moment in the existing foundation. The deeper the conduit is located, the smaller the bending moment tends to be in the existing pile foundation (see Figure 11 and Figure 12).

Changes in bending moment due to the movement of the slurry machine are shown in Figure 11 and Figure 12. The bending moment increases as the slurry machine approaches the existing foundation and continues to rise as it moves past the foundation. However, at the pile head, a decrease in bending moment begins when the slurry machine has moved 18 m beyond the foundation, particularly when the conduit is positioned at a depth of 0.5Doc. At a depth of 34 m until 43 m, a reduction in bending moment is observed when the slurry machine moves 6 m away from the existing pile foundation.

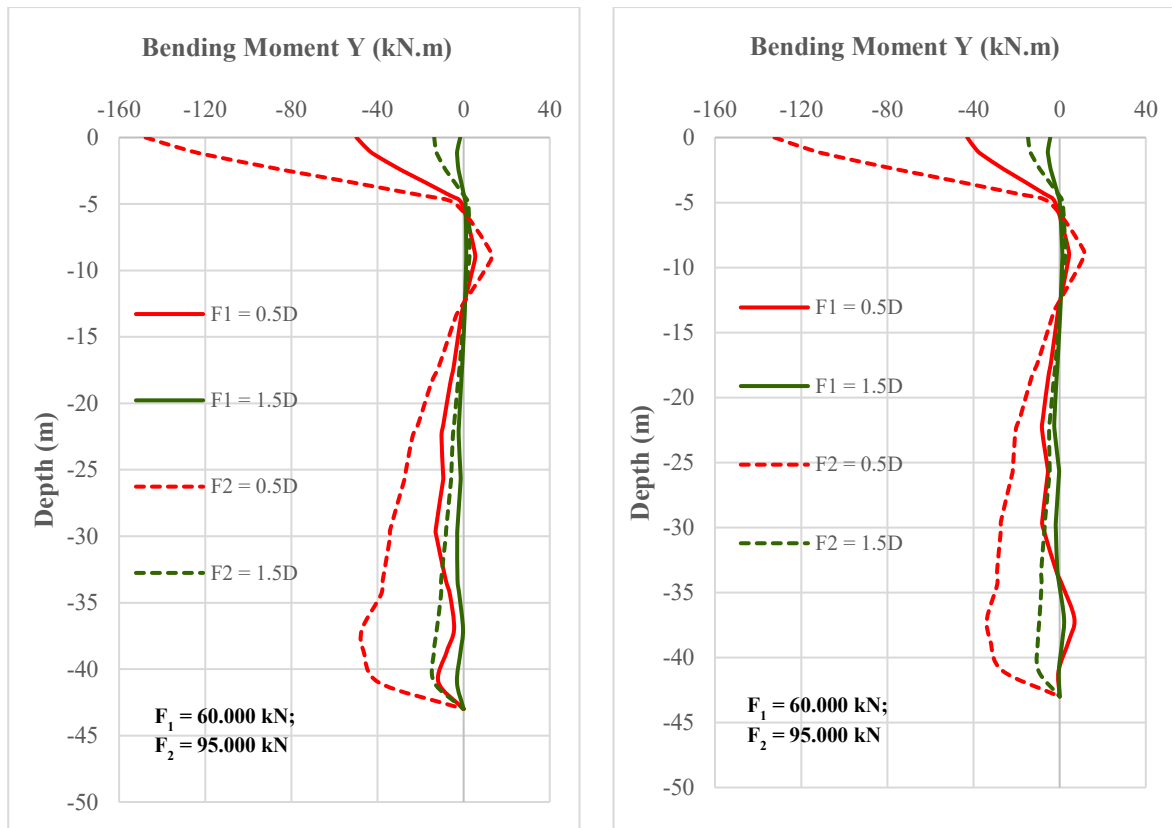


a. First Tunneling (15 m Before the Pile 4)



b. Tunneling Beneath the Pile 4

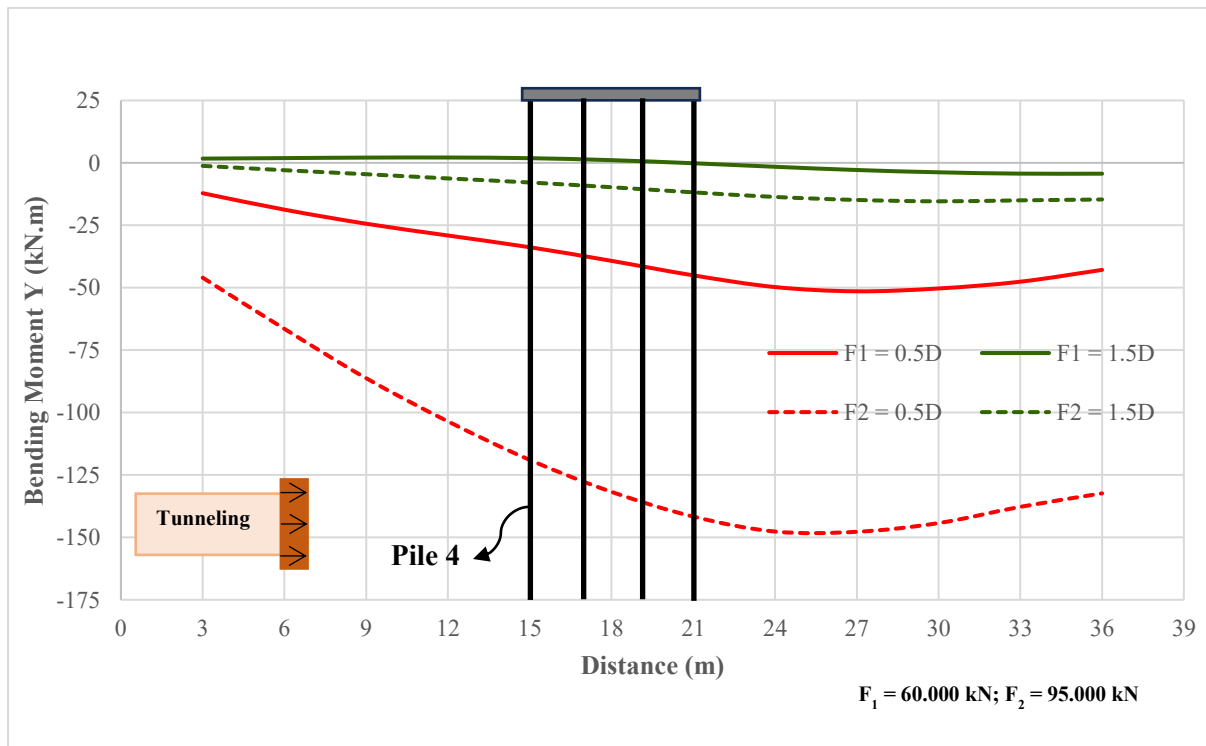
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c. Tunneling 9 m Away from the Pile 4      d. Tunneling 21 m Away from the Pile 4

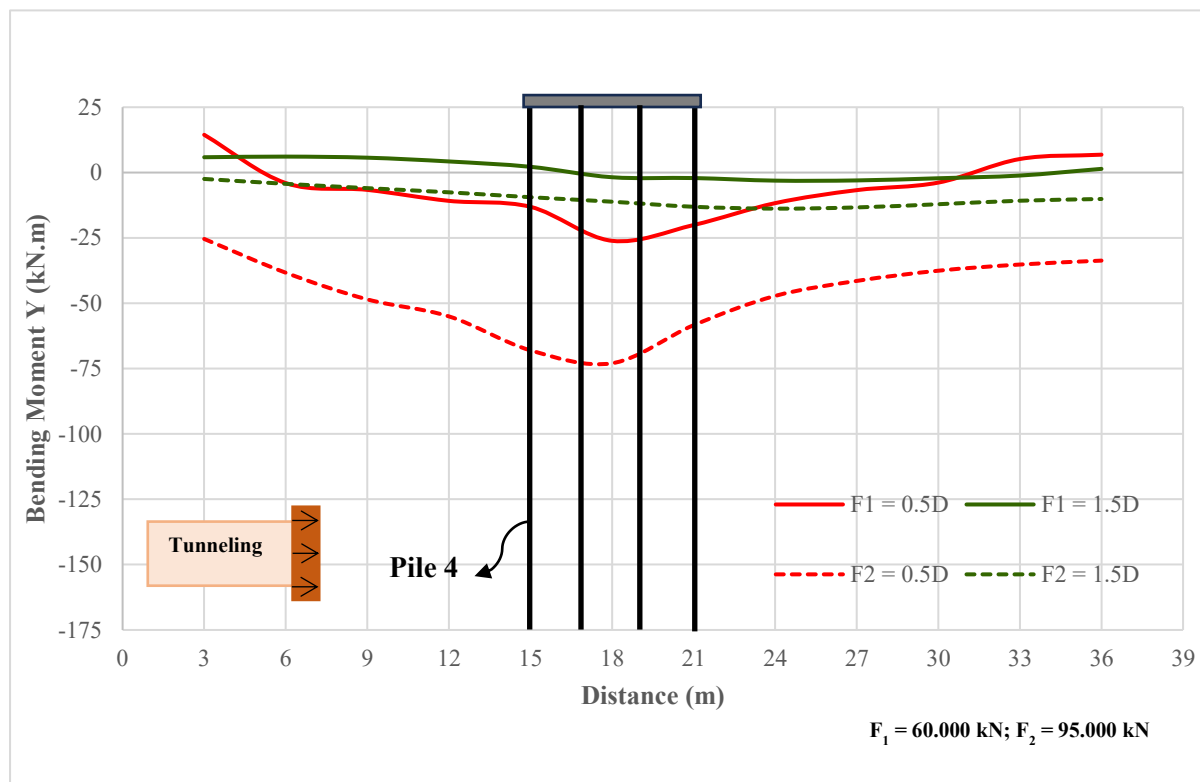
**Figure 10. Bending Moment Due to Variations in Total Thrust Force (F)**

Source: Bending moment output (Y axis) from tunneling stage analysis, 2024



**Figure 11. Bending Moment at Pile Head**

Source: Maximum moment data at the pole head (Pile 4) with fixed-head condition, 2024



**Figure 12. Bending Moment of the Pile Foundation at 34 m to 43 m**

Source: Distribution of bending moments in the bottom third of the mast from the MIDAS simulation, 2024

The analysis also shows that the  $F$  significantly affects the magnitude of deflection, settlement, and bending moment in the existing pile group foundation. The greater value of  $F$ , the larger the resulting deflection, settlement, and bending moment. In addition, the depth of the tunneling also influences the foundation response. As the conduit depth increases, the deflection, settlement, and bending moment in the existing pile group tend to decrease.

The settlement analysis indicates that settlement is more dominant than lateral deflection, making it the primary concern in evaluating foundation performance. During the initial stage of tunneling, significant settlement occurs immediately, ranging from 8.80 mm to 9.09 mm. After this initial phase, the rate of settlement decreases, indicating that the most critical impact of the tunneling activity on the foundation occurs at the early stages of tunneling.

The bending moment analysis shows that the most significant impact occurs at the pile head. This happens because a tensile force acts on the pile tip in the same direction as the slurry machine's movement, causing the pile tip to move along with the tunneling. In contrast, the pile head moves in the opposite direction. This difference in movement creates a bending effect that can lead to rotation or inclination of the pile cap. This condition becomes more serious because the existing bridge superstructure is a statically indeterminate system. This means that any movement in the pile group foundation can affect how internal forces are distributed in the structure above. The risk increases if there are no tie beams connecting the foundation columns, since the structure lacks side support to resist rotation and movement between the piles

Therefore, if structural reinforcement is to be implemented, additional reinforcement should be concentrated in the pile head area to enhance the strength and stability of the foundation system.

### CONCLUSIONS

This study examines the effects of underground tunneling using slurry machines on existing bridge foundations through numerical modeling in MIDAS GTS NX, concluding that Total Thrust Force (F) is the primary factor influencing foundation response, with higher thrust forces causing increased deflection, settlement, and bending moments in pile group foundations. Additionally, deeper conduit placement below the pile tip reduces these adverse impacts, while the initial tunneling distance—particularly about 15 meters before pile 4—critically affects early settlement due to soil disturbance. The maximum bending moment occurs at the pile head, indicating the need for reinforcement there, especially since the absence of tie beams in statically indeterminate structures increases superstructure vulnerability. Recommendations include reinforcing the pile head via sliding reinforcement or concrete jacketing, optimizing tunneling parameters by maintaining F between 60,000–80,000 kN and conduit depth at or beyond 1.5 times the pile diameter (Doc), and installing tie beams to improve load distribution. For future research, dynamic effects, compensation grouting, and real-time monitoring during construction should be explored to further enhance foundation safety. These findings offer risk-based technical solutions with the potential to reduce repair costs by up to 40% in similar projects.

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