CIVED
Journal of Civil Engineering and Vocational Education

EISSN: 2622-6774
Vol 11 No.2 June 2024
http://cived.ppj.unp.ac.id/index.php/CIVED

Analysis of Reinforced Concrete Pipe Strain Due to Jacking Force Case Study: Sudetan Ciliwung River Project to the East Flood Canal

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Received 11th April 2024; Revision 23th May 2024; Accepted 29th June 2024

ABSTRACT

Pipe Jacking is an innovation in trenchless technology that has been utilized in various sectors including municipal wastewater systems, oil and gas transportation, and hydraulic engineering. One of the critical aspects to ensure the success and safety of the pipe jacking process is strain monitoring. This study discussed the strain characteristics of reinforced concrete pipe structures during pipe jacking. The analysis was conducted using a numerical approach, which compared to field monitoring. Field strain monitoring was performed by strategically placing strain gauges along the pipe during the jacking operation, resulting in real-time data on deformation and pressure values. When the strain was monitored, the numerical test was conducted simultaneously using finite element analysis of Rocscience 3D. Those activities were done to consider the interaction between the reinforced concrete pipe and the surrounding soil. The strain analysis results indicated that the pipe responded during the pipe jacking process. The values of strain were various, depending on jacking force, condition of excavated soil layers, and distance between twin tunnels. The maximum stress occurred at the beginning of jacking process, when the pipe infiltrated into the soil with stress value of 512 kPa.

Keywords: *Strain Analysis; Pipe Jacking; Finite Element.*

INTRODUCTION

In recent years, urban underground spaces, such as utility tunnels, subway stations, and underground commercial areas develop rapidly [1]–[3]. Pipe jacking technology is extensively applied to the construction of large-diameter pipes, city pipeline corridors, and underground passages. due to the minimum excavation and low environmental impact [4]. Pipe jacking generates specific soil responses, particularly in jacking constructions that involves large sections in complex soil layers, causing greater disturbance to the soil in the installation areas [5], [6]. Pipe jacking is an innovation in trenchless technology, utilizing a cutting shield to install pipes by pushing sections from a drive shaft into a bore formed, so it can construct continuous tunnel lining [7]. The existing research on pipe jacking focused onpipe jacking interaction with circumstances, including theoretical analysis [8]–[12], field monitoring, and the combination of various numerical theories [13]–[20].

One of the critical aspects to ensure the success and safety of the pipe jacking process is strain gauge monitoring. In this research study, strain gauge monitoring was conducted to determine the deformation of the pipe due to jacking forces during the pipe jacking process. Jacking force played a crucial role in the pipe jacking process as it moved the pipe through the soil. Hydraulic jacks applied force to the front end of the pipe, which was then distributed along the pipe, causing it to move forward. When the jacking force was distributed along the pipe, it induced strain within the pipe material.

This project was located between two rivers running through the densely populated urban area of Jakarta, Indonesia: the Ciliwung River and the East Flood Canal (KBT), with a total length of 587.785 meters. Excavation and tunnel construction in the underground area using the pipe jacking method, where ongoing infrastructure activities take place is highly suitable for this project. The pipes were excavated and pushed using the Earth Pressure Balance (EPB) tunneling method with an Earth Pressure Balance machine. The concept of "Pipe Jacking Technology" illustrates a repetitive process where the front head of the EPB machine uses water to cut through soil or break rock, transforming it into a slurry that can be moved or disposed of. The EPB machine's head followed the pipe after pushing it into a certain distance and performed jacking in the same direction as the machine's movement.

The analysis was conducted only during the pipejacking process. There were 40pipes whichpreviously installed along the pipe jacking route.This study monitorred the pipe number 42. The actual pipe area in the field was designed as a twin tunnel. The twin tunnel was modeled according to the field conditions, with a distance of 1.4 meters between the pipes.

METHOD

This research began with collectingrelevant secondary data and several related research sources as references to determine the used method. Strain analysis in the field and numerical analysis were conducted simultaneously during the pipe jacking process.

Field Monitoring

The used pipes were precast reinforced concrete pipes, which specifications are listed in Table 1. The maximum diameter of the EPB machine was 4.07 meters, with the pipes having a diameter of 4.05 meters, an internal diameter of 3.5 meters, and a wall thickness of 0.275 meters, as shown in Figure 1. Each pipe section was longitudinally assembled with two layers of main reinforcement. Each layer consisted of 30 reinforcement bars with a diameter of 16 mm, arranged symmetrically with a spacing of 150 mm. The circular reinforcement had different specifications: 8 circular reinforcements with a diameter of 22 mm, spaced at 120 mm, and 5 main outer circular reinforcements with a diameter of 19 mm spaced at 200 mm, as shown in Figure 1.

Table 1. Pipe Specifications

Concrete Material (MPa)	f_c' 50
Steel Material (MPa)	BJTS-420B, f_y: 420
Internal Diameter of Pipe (m)	3.5
External Diameter of Pipe (m)	4
Pipe Wall Thickness (m)	0.275
Pipe Length Per Segment (m)	2.5

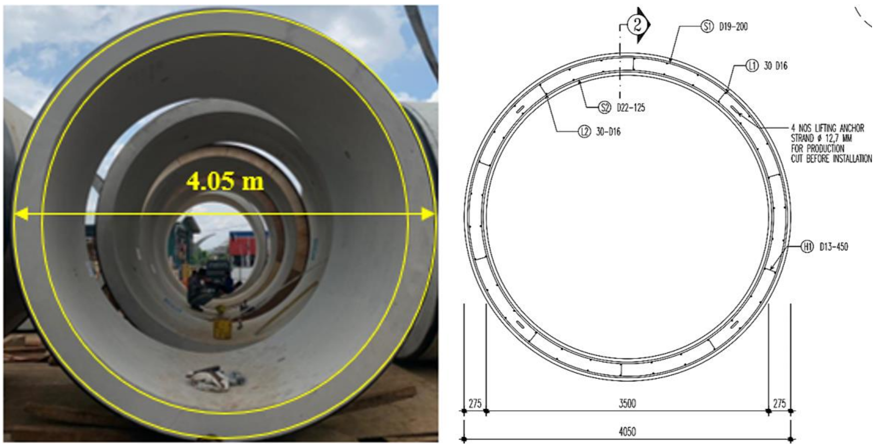

Figure 1. (a) Pipe in the Field (b) Pipe Structure

Excavation was carried out in stages, with the jacking machine performing a jack every 0.5 meters/jack. Since the total length of the pipe segment was 2.5 meters, there were five jacking stages, with the jacking force and excavation length are detailed in Table 2.

Table 2. Jacking Force During the Pipe Jacking Process

Excavation Length (m)	**Jacking Force (t)**
0.0 – 0.5	400
0.5 – 1.0	400
1.0 – 1.5	440
1.5 – 2.0	440
2.0 – 2.5	400

Strain Sensors

Strain sensors were installed on the pipe reinforcement, which was done before the pipe was casted at the factory. A total of 6 sensors were installed, with 4 sensors placed longitudinally and 2 sensors placed radially. The installation of the radially oriented sensors is shown in figure 2 (a), while figure 2 (b) shows the installation of the longitudinally oriented sensors. Arc Weldable strain gauges were used, as they were preferred for long-term strain measurement on steel members such as tunnel linings, arches, piles, and similar structures [21].

Figure 2. (a) Radial Strain Sensor Placement (b) Longitudinal Strain Sensor Placement

Numerical Method

The jacking force was evenly distributed to the circumference of the pipe layer and worked on the most recent layer. Figure 3 illustrates that Pipe 1 was the non-jacking pipe or the pipe that had been jacked, while pipe 2 was the jacking pipe, or the monitored pipe during the pipe jacking process.

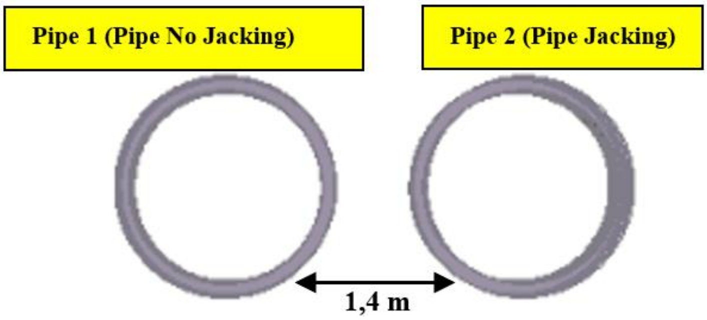

Figure 3. Twin Tunnel Pipes

The soil layers from the inlet area to the end of shaft were divided into 6 sections: BH-01, BH-03, BL-3, BL-4, BL-5, and BL-6. These sections were selected based on the bore log testing locations. During the field strain monitoring and numerical model analysis, monitoring was only conducted in the area where pipe jacking was taking place, specifically in the driving shaft of inlet area BH-01 (pipe 42), as shown in Figure 4.

In this study, numerical modeling constraints with twin tunnels were used, with the surrounding area modeled as undisturbed. The horizontal boundary condition was set at 25 meters from the outer side of the tunnel to ensure proper application of pipe-soil interaction during the pipe jacking process, using standard fixed supports. The total model height was 33 meters, determined to reach stable soil. The pipe depth was 11.3 meters, with an outer diameter of 4 meters and a wall thickness of 0.275 meters. The pipe condition was modeled for only one pipe segment, and a 3D strain model was used, considering the interaction between the pipe and the soil.

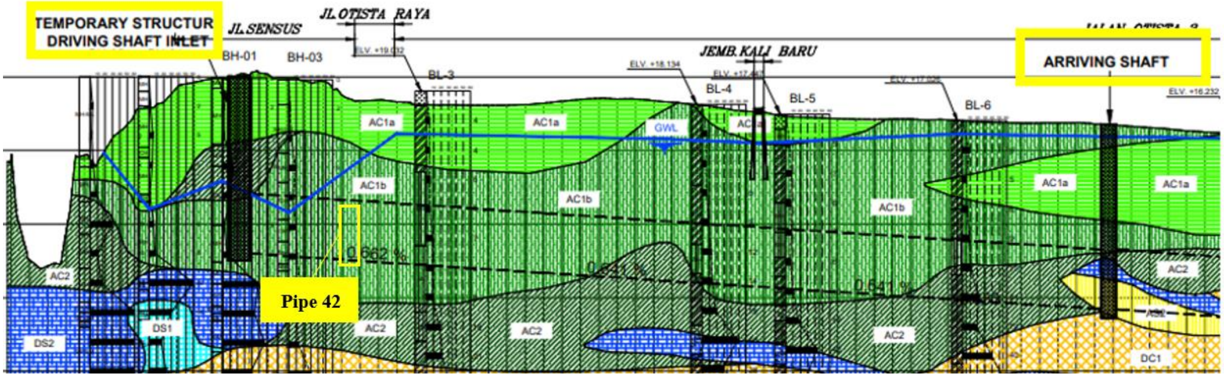

Figure 4. Pipe Stratification

The setup mode used the Mohr-Coulomb model, a failure theory regarding materials, which states that material failure is caused by a critical combination of normal stress and shear stress. Loading was carried out using 6 thrust jacks, resulting in a normal jacking speed of 15 mm/min. The thrust jacks are illustrated in Figure 5.

The front pipe had been jacked in the previous time. Pipe jacking was performed in stages along 0.5 meters per jacking, with a total of 5 jacking stages conducted in the field. The first jacking stage, or stage 1, required a force of 400 tons along 0-0.5 meters on the pipe. During stage 1, the excavating machine or EPB machine was at STA 0+105 (Figure 6), with 41 pipes behind it in soil classification AC1b. The parameter detail is presented in Table 3 and this was applied to the subsequent stages.

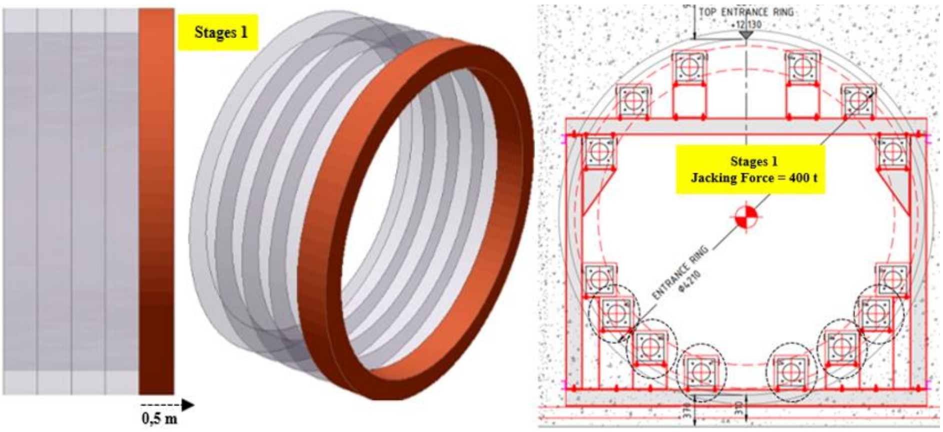

Figure 5. Pipe and Thrust Jack at Stages 1

The initial element loading was selected based on field stress and pipe forces to demonstrate that the stress and self-weight had been modeled on the pipe. Subsurface statistics were modeled using the coordinates of the drilling locations and the depth of each soil layer according to field conditions. The distribution of water and soil pressure was modeled uniformly with the actual layers in the field.

Table 3. Detailed Parameters of Soil Classification AC1b

Parameter	**Unit**	**Soil Classification**
		AC1b
Consistency		*Soft to Medium Stiff*
Water Content	w_n	62.520
Bulk Density	γ_n	1.682
Specific Gravity	γ_w	2.615
Plasticity Index (IP)	%	133.94

RESULTS AND DISCUSSION

Field Monitoring and Numerical Results

Monitoring of the pipe was conducted during the pipe jacking process, with supervision only carried out when the pipe first entered the ground, or during the initial jacking process. Sensor values were recorded only during the initial jacking, which took place on November 21, 2023. The timing adjustments were made to correspond with the jacking process. Theoretically, greater stress is expected to occur at the pipe's end (Table 4).

Table 4. Strain Results on the Pipe

Sensor Point	**Stages 1 (με)**		**Stages 2(με)**		**Stages 3(με)**		**Stages 4(με)**		**Stages 5(με)**	
	Field	**Rs3**	**Field**	**Rs3**	**Field**	**Rs3**	**Field**	**Rs3**	**Field**	**Rs3**
1L	84	32	85	11	8	12	8	8	8	8
2L	10	12	9	7	6	10	6	5	6	7
3L	7	5	5	4	3	11	3	4	3	1
4L	63	8	62	8	8	12	8	11	8	32
5R	28	19	8	8	4	12	4	5	4	5
6R	72	26	72	10	35	10	35	7	35	25

Table 4 shows that the strain readings in the field and the numerical resultsvaried significantly in the first and second stages. However, this variation decreased in the subsequent stages. This condition was caused bythe alignment of the pipes. Although numerical analysis assumed perfecty aligned pipes, in reality, each pipe may not be entirely aligned, leading to stress concentration. However, as the jacking process was in progress, each pipe adjusted itself.

Displacement Twin Tunnel

Excavation of twin tunnels was likely to cause movement in the surrounding soil. Negro Arsenio (2005) stated that asymmetric behavior and increased volume loss mainly happened when the distance between pipes was close, as in this case, the soil around pipe 1 was disturbed and its stiffness reduced due to excavation. Monitoring results indicated that the sensors responded when the pipe was jacked or pushed into the ground (Figure 6).

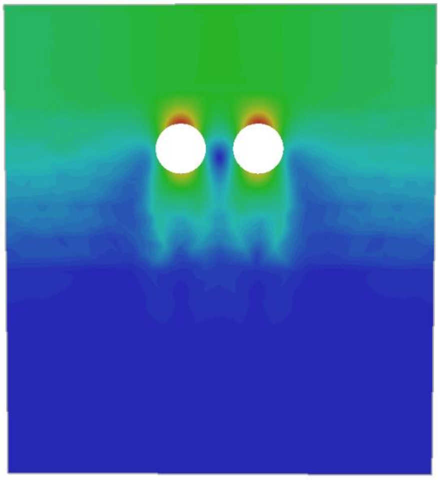

Figure 6. Pipe Displacement Results

Excavating pipe 2 under these soil conditions caused higher displacement and maximum displacement eccentricity towards pipe 1, where the soil was more disturbed. Pipe 1 had been jacked for a considerable time, but the soil around it was still disturbed by the pipe 2 jacking process. Therefore, the potential displacement caused by excavating pipe 2 could not develop unhindered due to the rigid support from pipe 1, resulting in a significant increase of pressure. On the other hand, pipe 2 was excavated in a field of distorted stress with pre-existing plastic zones, if the geotechnical conditions were poor, leading to a slight increase of pressure.

Figure 6 confirms that the presence of pipe 1 affected the excavation of pipe 2. Displacement tended to slightly increase and decrease depending on the jacking force applied and the soil layers excavated using the EPBM machine ahead (as shown in Figures 7 and 8). The numerical results indicated that the spacing between pipes and the type of layers in the front area were two most critical factors affecting the displacement and deformation of pipe 1 layers. Pipe 1 also influenced the deformation and horizontal displacement caused by the deep excavation of the second pipe. Analysis for pipes pushed through non-cohesive material, where the soil was assumed to collapse around the pipe, providing radial pressure forces around its circumference [23].

In the soil deformation results, deformations only occurred around the pipe assumed to collapse into the pipe, exerting radial pressure around it. Deformation colors were only in circles around and above the pipe, where the soil was in full contact with the outer part of the pipe, thus bearing the load from the surrounding soil. Deformation decreased progressively.

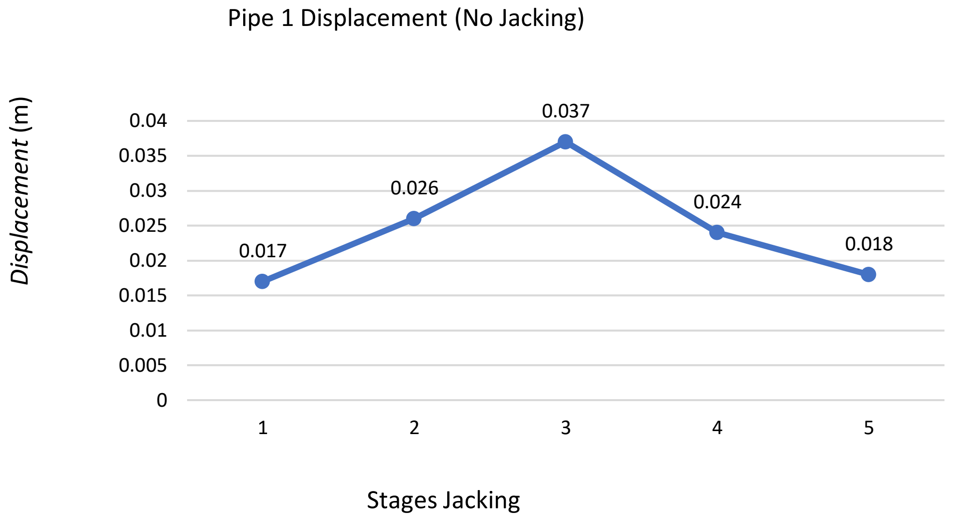

Figure 7. Pipe 1 Displacement Results (No Jacking)

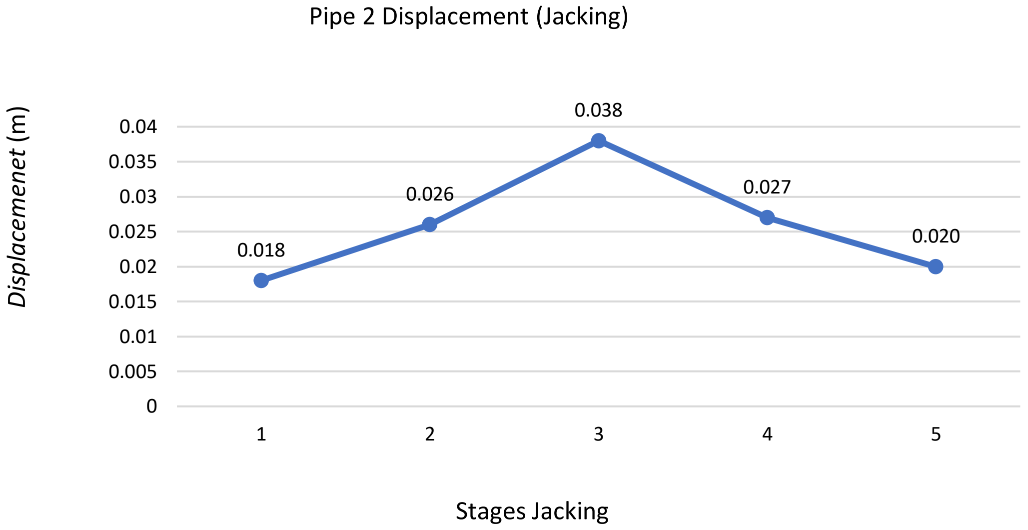

Figure 8. Pipe 2 Displacement Results (Jacking)

The strain values at the beginning of the pipe were very high due to the pressure of the first jacking load, causing adjustment between the pipe's main axis and the excavation. This could occur due to misalignment of the pipe during jacking or the initial jacking. Imperfectly straight pipes result in very high strain values at certain points or incomplete contact of jacking pressure with the soil. This might also happen because the slurry had not uniformly covered the pipe surface, leading to high friction during the jacking process. Figure 9 shows the recorded stress at every stage during the pipe-jacking process.

Stress on the Pipe

The maximum stress occurred at the base of the pipe, reaching 512 kPa at the pipe end. Various soil conditions could alter the interfacial stress along the tunnel. The stiffer response of clayey soil compared to loose sand lead to significant radial interfacial stress.

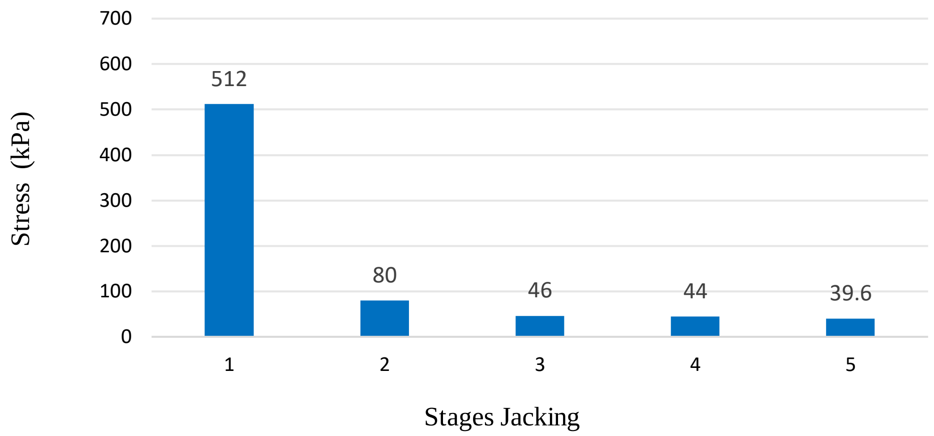

Figure 9. Stress Results on the Pipe

Strain at Sensor Point 3L

Strain gauges were installed on the pipe along a line perpendicular to the load application position (strain position 3L) (Figure 11). This 3L strain position measured the principal compressive strain parallel to the direction of the applied load. Stress varied rapidly over short distances of less than 500 mm and maight be a function of local variations in the excavation profile.

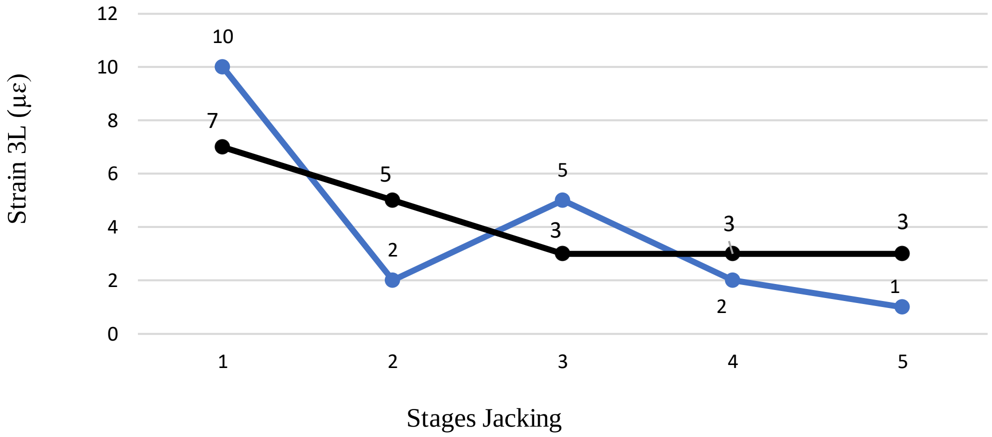

Figure 1. Strain Results on Pipe at 3L Area

The primary uncertainty in pipe jacking arised because pipe alignment was imperfect. Load distribution among pipes was uneven and the interaction between soil and pipe created frictional forces that impeded the forward movement of the pipe string significantly. These two effects interacted to increase jacking loads and create stress concentrations on the pipes. Static analysis in this section primarily focused on pipe strain during pipe jacking. Mudsand collapse occurred at the top of the pipe, while pressure on the sidewalls varied from zero to significant values depending on the direction and extent of pipe misalignment. Peak values typically occurred midway along the pipe's length, depending on the short length and corresponding maximum deviation from the line and height.

CONCLUSION

The analysis revealed a response to the jacking force during pipe jacking. Strain results in the field and numerical results in the first and second stages varied significantly, but this variation decreased in subsequent stages. The displacement results of the twin tunnels indicated an interaction effect when two adjacent twin tunnels with close distance were excavated sequentially. The displacement of pipe 2 was higher than that of pipe 1. Pipe 1 affected horizontal displacement due to the excavation of pipe 2. The maximum stress arising from the jacking process was 512 kPa, which was much lower than the permissible concrete stress.

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