

Stress and Deformation Analysis of Existing Underground Pipelines During Soft Soil Consolidation with Prefabricated Vertical Drains and Vacuum Preloading

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Abstract — This study assesses vacuum-assisted soft-clay improvement using Prefabricated Vertical Drains (PVD) and the consequences for an in-service buried pipeline along a planned toll-road. A PLAXIS 3D descriptive-quantitative model couples ground consolidation with soil-pipeline interaction: PVDs at 1.5 m spacing to 22 m depth beneath a sand blanket, a 50 kPa vacuum, and embankment loading in four 1 m lifts (vacuum-reduced equivalent surcharge ≈ 74 kPa; fill ≈ 4 m). The ground reaches $\sim 90\%$ consolidation with ≈ 3.1 m total settlement and a low post-dwell rate. Pipeline demands remain below the allowable: governing stress 381 MPa versus 435 MPa (minimum FS ≈ 1.1), despite peak bending, shear, and axial actions. Differential settlement of ~ 100 mm arises near transitions between loaded and lightly loaded zones. Practically, the vacuum-PVD scheme accelerates consolidation to meet schedule while keeping pipeline stresses within code limits; however, local transitions require attention—e.g., staged sequencing, short transition slabs, and targeted monitoring—to limit differential movements during surcharge removal and early operation

Keywords: prefabricated vertical drain; vacuum preloading; stress and deformation analysis.

I. INTRODUCTION

The rapid expansion of highways over soft, compressible soils has increased the need for efficient ground improvement methods that minimize construction time while protecting existing infrastructure, including buried pipelines. These pipelines must remain operational during construction, which presents a challenge due to the effects of embankment loading and accelerated consolidation. Prefabricated vertical drains (PVD) and vacuum preloading are commonly used to speed up consolidation, but the impact on pipeline integrity must be carefully evaluated, especially under realistic degradation scenarios. (Aslam & Gofar, 2022).

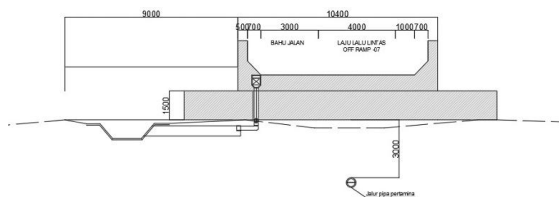


Figure 1. Existing conditions of the pipeline and pavement

Although previous research has studied PVD and vacuum preloading separately or together, few have integrated these methods with pipeline structural models in 3D finite-element analysis.

Furthermore, guidance is limited on how different construction stages (such as load magnitude and duration) influence consolidation and the pipeline's performance. This study aims to address these gaps by evaluating the effects of PVD and vacuum preloading on soil consolidation, pipeline stresses, and safety under realistic conditions.

The study uses a calibrated PLAXIS 3D model to assess pipeline performance during ground improvement, focusing on consolidation rates, pipeline bending, shear, and axial forces. The findings provide practical insights, including an integrated modeling approach, guidelines for staging and consolidation, and safety assessments of pipelines under degradation. This paper contributes to better design practices by linking construction stages with consolidation targets and offering safety checks for pipeline integrity.

II. LITERATURE REVIEW

Field and numerical studies consistently show that combining Prefabricated Vertical Drain (PVD) with Vacuum Preloading accelerates primary consolidation by shortening drainage paths and raising effective stress without adding large surcharge height. In a toll road corridor on very soft soil, organic, water saturated clays in south sumatra, (Gusnadi et al., 2024). The study

couples field monitoring with finite-element modelling that represents radial flow and drain smear via an equivalent-permeability approach. Measured responses show >400 mm settlement achieved in <90 days, and ≥80% degree of consolidation within roughly the same period under a vacuum level of ~80 kPa; concurrently, lateral deformation remained within acceptable bounds, indicating adequate global stability during staged embankment works (Gusnadi et al., 2024).

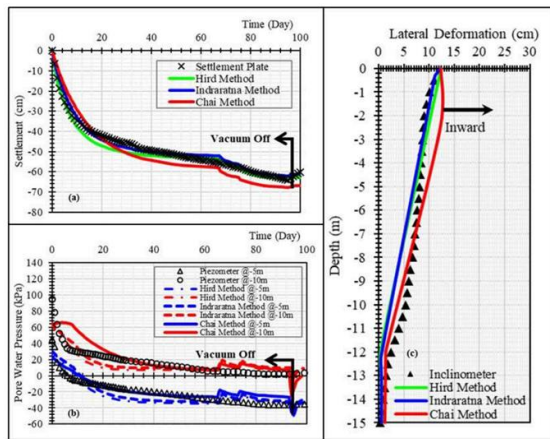


Figure 2 Comparison of monitoring data against analysis results.

These results support the suitability of PVD–vacuum systems for schedule-driven soft-ground projects and highlight key design levers: permeability anisotropy, smear parameters, vacuum magnitude, and staging/dwell-time control. At the same time, most reported applications including this case—focus on ground response and surface stability; explicit, coupled evaluations of buried-pipeline demands (bending, shear, axial actions) during accelerated consolidation remain limited—motivating the present study’s integrated soil–pipeline modelling (Gusnadi et al., 2024).

Ground compaction during installation can elongate the vertical diameter of flexible buried pipes known as the “peaking” effect yet conventional codes typically consider only vertical overburden–induced compression and neglect this installation-locked deformation. (Zhang Y. , 2024) addressed this omission with full-scale tests on a Grade X52 steel pipe (D = 600 mm, t = 12.7 mm) and companion finite-element analyses. They distinguished the response due to side compaction (which tends to vertically elongate the pipe and produce tensile crown stresses) from that due to external surface loads

(which vertically shorten the pipe and produce compressive crown stresses). A key design message is that the initial peaking from installation can materially influence subsequent live-load response and should be included in safety checks. (Zhang Y. , 2024).

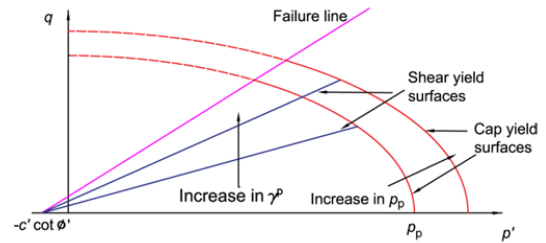


Figure 3 Shear and cap yield surfaces for HS model. Source: (Zhang Y. , 2024)

Numerical work (PLAXIS, HS model with $R_{inter} = 0.7$) reproduced measured trends and enabled a parametric study on soil water content, pipe wall thickness, compaction pressure, and lift thickness. Higher water content (softer soil) increased peaking up to ~14% water content, beyond which differences diminished; greater wall thickness increased bending moment but reduced stress ($\propto 1/t^2$); higher compaction pressure amplified peaking yet still stayed well within service limits; and larger lift thickness reduced peak crown stresses and lateral earth pressures at springline.

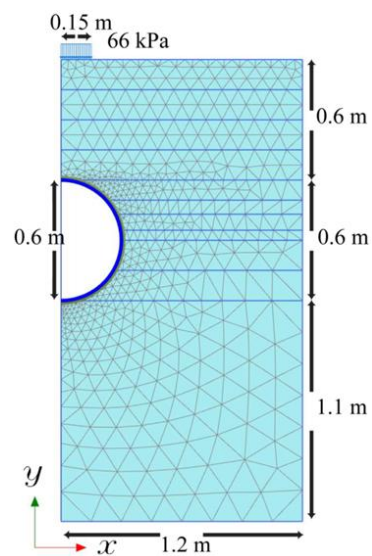


Figure 4. Two dimensional finite element method

The paper also elucidated earth-pressure redistribution (negative/positive arching) tied to rebound after compaction and subsequent surface

loading—mechanisms that reconcile why measured vertical pressure at the crown can fall below or exceed prism load, depending on stage and stiffness. Collectively, these results provide quantitative envelopes for installation-locked deformation, highlight stage-dependent soil–pipe interaction, and supply practical levers (water content control, lift thickness, compaction energy, wall thickness) to manage pipeline integrity during construction. (Zhang Y. , 2024)

III. METHOD

This study employs a descriptive–quantitative approach using three-dimensional numerical modeling to evaluate the performance of soft clay improved with Prefabricated Vertical Drains (PVD) and vacuum preloading. It further couples the ground-improvement analysis with the response of an existing buried pipeline by quantifying pipe stresses and assessing safety factors to verify in-situ pipeline integrity.

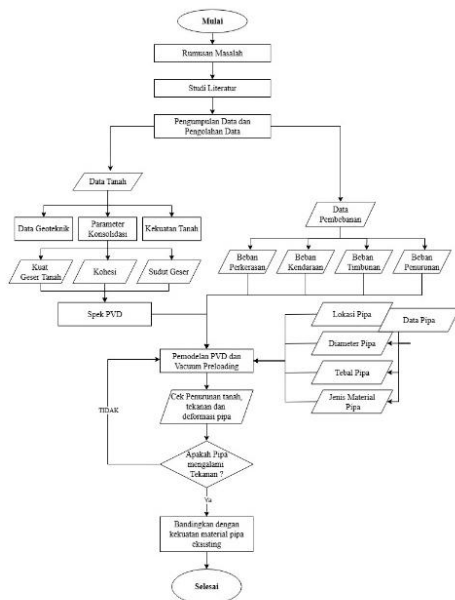


Figure 5. Flowchart of the research

A. Data Analysis

The data analysis conducted in this study can be seen in Figure 5, where the analysis steps taken are as follows:

1. Interpretation of soil data;
2. Assesment of embankment fill requirements for PVD and Vacuum Preloading, Including PVD spacing;
3. 3D numerical modeling using Plaxis 3D;
4. Settlement analysis of soft soils;

5. Pipeline stress analysis;
6. Safety factor (SF) evaluation for the pipeline.

B. Numerical Modeling

Numerical simulations were performed using Plaxis 3D, a finite element software for geotechnical applications. The model geometry consist of soil layers, pipe line element represented by plate structural element and vertical drains representing PVD installation as shown in Figure 6. Vacuum preloading was simulated by applying negative pressure to accelerate consolidation. Boundary condition were set to ensure stability and replicate field conditions. The mesh was refined around the pipeline to capture localized stress and deformation accurately.

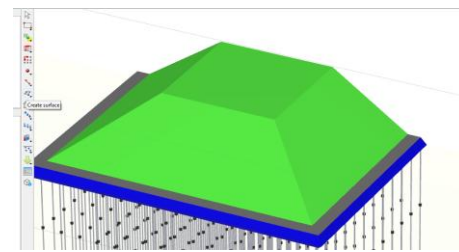


Figure 6. Domain and boundary condition

1. Height of Embankment Design

The embankment requirements in the PVD and vacuum preloading analysis are evaluated with respect to the anticipated service loads during the operational period, which include embankment self-weight, traffic loads, pavement loads, and settlement compensation, as summarized in Table 1 below.

Table 1 Summary of required load (service condition)

Load For Embankment Height		
Embankment Load	51	kPa
Traffic Load	15	kPa
Pavement Load	20	kPa
Settlement Compensation	17	kPa
Total	103	kPa

After the service loads are defined, a load ratio (factor) of 1.2 is applied to enhance construction safety and to ensure that service conditions are adequately represented during the preloading and vacuum-preloading phases. With this factor, the design equivalent surcharge becomes 123.6 kPa, corresponding to a planned embankment height of 7.3 m.

With Vacuum preloading capacity of 50 Kpa, part of Surcharge demand is supplied by the vacuum

itself. Therefore, the required preloading surcharge become 73,6 kPa accordingly, the final embankment height required is taken as 4 m during the PVD and Vacuum Preloading.

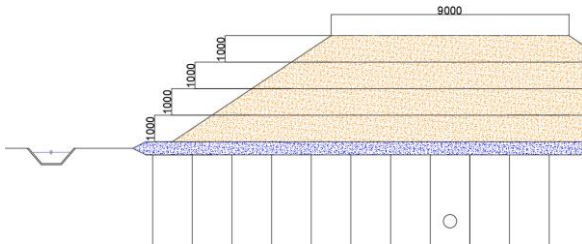


Figure 7. Height of embankment

2. Spacing PVD

The PVD layout uses 1.5 m spacing to a 22 m depth (line drains tied to the sand blanket), accelerating consolidation while limiting differential settlement and safeguarding the existing buried pipeline.

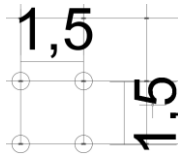


Figure 8. Spacing PVD

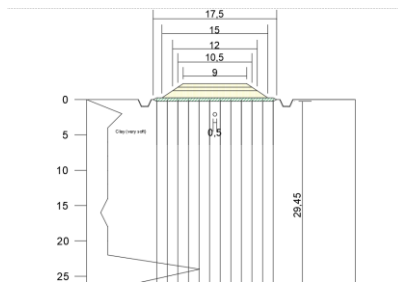


Figure 9 Depth of PVD

3. Material Pipeline

In PLAXIS 3D, the existing buried pipeline is modeled with plate elements, which capture pipe behavior by specifying wall thickness, material

modulus, and yield strength consistent with the pipeline's properties.

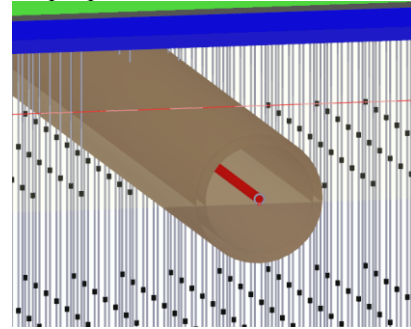


Figure 10. Pipeline Model in Plaxis 3D

In the pipeline analysis, soil structure interaction is represented using positive and negative interface element with a specified R_{inter} on both sides of the pipe in plaxis 3D. this setup captures relative slip, shear transfer, and contact behaviour between the soil and the existing buried pipeline.

4. Material Model

Modeling utilizes the Mohr-Coulomb model, where input parameters are obtained through analysis of secondary data.

5. Stage Construction

The modeled stage-construction sequence is as follows:(1)initial stress and groundwater conditions; (2)installation of PVDs, placement of the sand blanket, and application of vacuum preloading; and (3)placement of embankment fill in four stages, each with a 1 lift height.

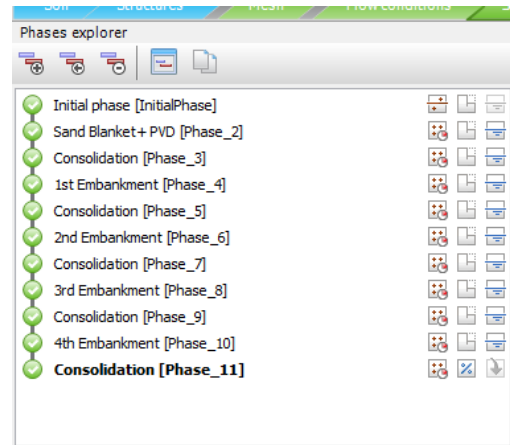


Figure 11. Stage construction on Plaxis 3D

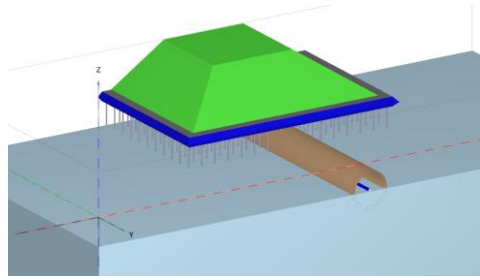


Figure 12 Full model of PVD vacuum preloading and existing underground pipeline

IV. RESULTS AND DISCUSSION

Interpretation of Soil Data and Design Parameters Based on the data obtained, the subgrade soil conditions were interpreted by compiling soil stratification for each layer, as shown in Table 2 and Figure 13.

Table 2. Soil stratigraphy

Layer	Depth (m)	N-SPT	Soil Type	Kategori (clay/sand)	
1	0	-28	3	Clay Silt	V. soft
2	-28	-45	35	Clayey sand	M.Dense
3	-45	-54	20	Silty clay	Stiff
4	-54	-58	55	Clayey sand	Dense
5	-58	-65	35	Sandy clay	V.Stiff

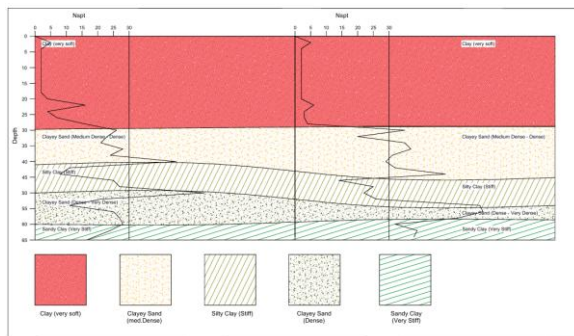


Figure 13. Soil stratigraphy

Based on existing soil conditions, data interpretation was performed to obtain design parameters as shown in the table. These values were derived from various empirical correlations compiled from literature and previous studies. Reasonableness checks, cross-validation between correlations, and sensitivity analysis were performed, particularly for E, cu, φ, and v before use in modeling.

Table 3. Design parameter (unit weight and void ratio)

Layer	γ (kN/m ³)	γ_{sat} (kN/m ³)	Cu (kPa)	C' (kPa)
1	13.0	14.5	16	2
2	19.0	20.5	-	3
3	17.5	19.0	90	5

4	20.0	21.0	-	6
5	19.0	20.0	150	6

Table 4. Design parameter (stiffness)

Layer	ϕ' (°)	e_o	Kz (m/s)	Ky=Kx (m/s)
1	18	2.72	3.00E-10	6.00E-10
2	37.5	0.60	5.00E-06	1.00E-05
3	16	0.80	3.00E-09	6.00E-09
4	40	0.55	1.00E-05	2.00E-05
5	16	0.80	3.00E-09	6.00E-09

Table 5. Design parameter for fill material

Layer	γ (kN/m ³)	γ_{sat} (kN/m ³)	ϕ' (°)	e_o	E50 ^{ref}	K
Fill Material	16	17	30	0.60	10.000	8,64

Source: (Gusnadi et al., 2024)

Table 6. Geogrid parameter

Index Properties	Units	Value
Polymer	[-]	High Density Polyethylene
SLS T _{cs}	[kN/m]	30.86
Unit Weight	[kN/m ²]	0.98
Roll Width	[m]	1.3
Roll Length	[m]	50

Source: Tensar (2025)

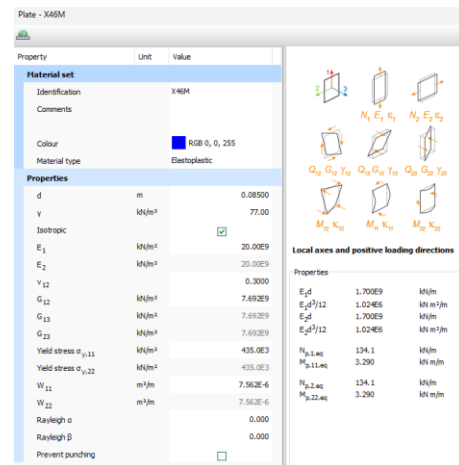


Figure 14. Material properties for underground pipeline

Settlement and Deformation Pattern

The PLAXIS-based numerical analysis yields three primary outputs: (i) consolidation time and settlement, (ii) excess pore-water pressure dissipation, and (iii) stress resultants in the existing buried pipeline (axial force, bending

moment, and shear). The settlement results—including total.

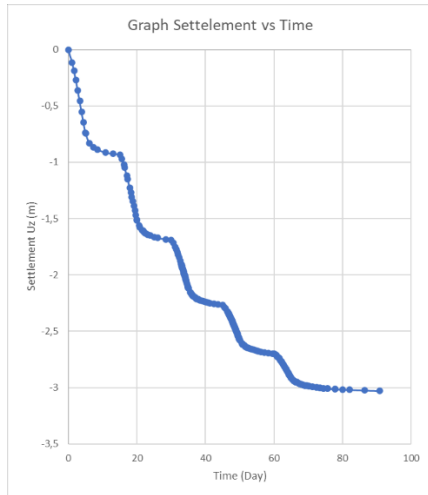


Figure 15. Consolidation time and settlement

The consolidation-settlement curve indicates staged settlement underground improvement with Prefabricated Vertical Drains (PVD) and vacuum preloading. After PVDs were connected to the sand blanket, radial drainage began while excess pore pressure (Δu) remained high initially. Four successive 1 m preload lifts produced cumulative settlements of about -0.90 m (10 days), -1.60 m (10 days), -2.10 m (10 days), and -2.60 m (10 days). A final dwell with no additional load allowed consolidation to progress slowly toward -3.10 m, corresponding to 90% consolidation and a low residual settlement rate.

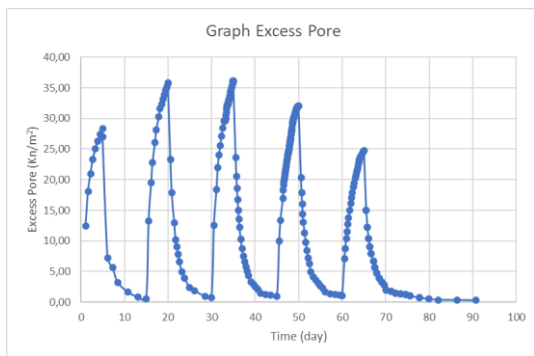


Figure 16. Graph excess pore pressure

The excess pore-pressure (Δu) graph captures how PVD and vacuum preloading accelerate consolidation during staged construction. Each sharp spike marks the start of a new embankment/vacuum stage, when total stress rises and Δu jumps (30–35 kPa); the subsequent exponential decay reflects rapid radial drainage

through PVDs toward the sand blanket under negative head. This spike-and-decay pattern repeats for each stage and is used operationally as a go/no-go control: the next lift is placed only after residual Δu has fallen to a small fraction of its peak and the dissipation rate has flattened. By the final dwell period, Δu approaches zero, indicating a high degree of consolidation and a low ongoing settlement rate conditions suitable for advancing construction while limiting differential settlement and pipeline demand.

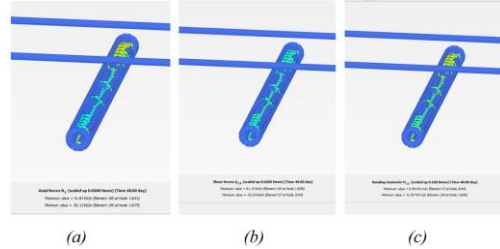


Figure 17. Output Plaxis 3d (a) axial force, (b) shear force, (c) bending moment

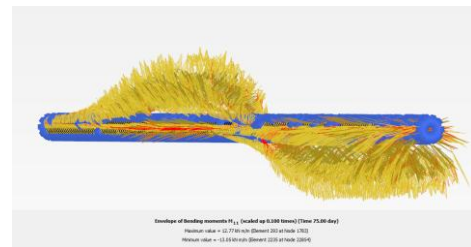


Figure 18. Bending moment

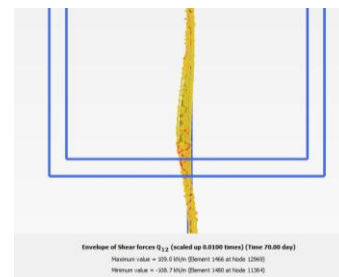


Figure 19. Shear force

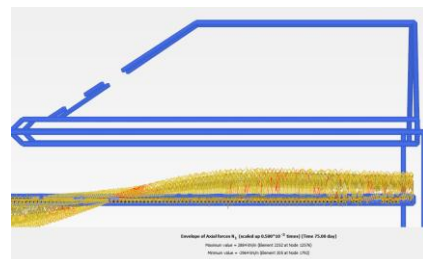


Figure 20. Axial force

Table 7. Resume of bending moment, axial force, and shear force

Bending Moment		Shear Force		Axial Force	
Max (Kn.m/m)	Min (Kn.m/m)	Max (Kn/m)	Min (Kn/m)	Max (Kn/m)	Min (Kn/m)
2,13	-2,26	27,71	-28,77	514,4	-505,9
2,15	-2,26	27,42	-28,45	511,9	-499,1
4,83	-4,83	52,39	-52,29	1103	-1132
4,82	-4,83	52,08	-51,99	1112	-1129
7,64	-7,52	74,03	-74,85	1700	-1776
7,64	-7,52	73,76	-74,54	1700	-1775
10,39	-10,33	95,5	-98,5	2315	-2384
10,39	-10,33	95,5	-98,49	2315	-2384
12,86	-13,05	115,4	-119,5	2884	-2964
12,86	-13,05	115,4	-119,6	2884	-2964

The stress analysis of the existing buried pipeline during consolidation covering PVD installation shown in

Table , vacuum application, and staged preloading shows the following peak actions: a bending moment of 12.86 kN·m/m, a shear force of 115.4 kN/m, and an axial force of 2,884 kN/m. These values represent the maximum demands recorded across all construction stages.

Table 7. Safety factor

Tegangan Lentur	SF	Tegangan Geser	SF	Tegangan Aksial	SF
20	21,6	3,67	118,6	68	6,4
20,2	21,4	3,63	119,9	68	6,4
45,5	9,5	6,93	62,2	146	3
45,4	9,5	6,89	63,1	147	3
71,9	6	9,79	44,4	225	1,9
71,9	6	9,76	44,5	225	1,9
97,8	4,4	12,63	34,4	306	1,4
97,8	4,4	12,63	34,4	306	1,4
121	3,5	15,26	28,4	381	1,1
121	3,5	15,26	28,4	381	1,1

Based on the stress evaluation, the allowable stress for the pipeline is 63 ksi (≈ 435 MPa). The analysis shows that the governing maximum computed stress is 381 MPa, which remains below the allowable value. Accordingly, the minimum safety factor (SF) is 1.1. Safety factors reported in Table 7 are obtained by comparing the pipe's capacity with the corresponding bending, shear, and axial demands at each construction stage.

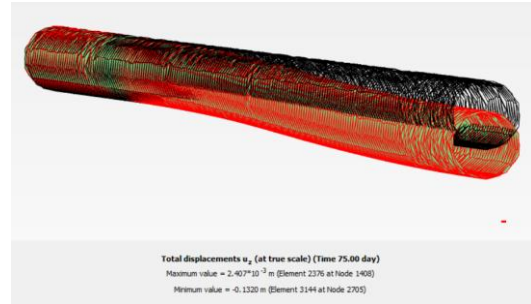


Figure 21. Differential settlement

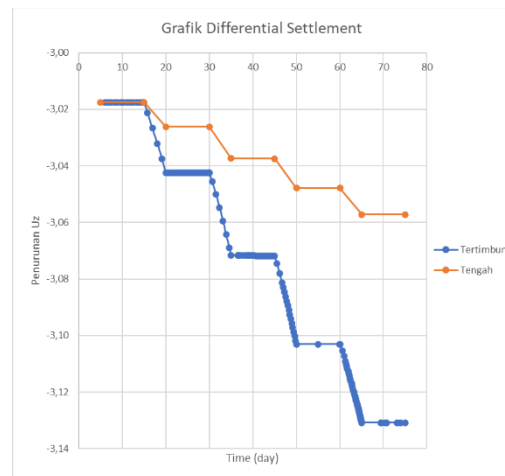


Figure 22. Graph of differential settlement

During consolidation, the existing buried pipeline experiences differential settlement Figure 21 because external loading conditions are not uniform along its alignment. Segments located beneath the embankment surcharge are subjected to higher effective stresses and therefore settle more than adjacent segments that are not loaded. Consequently, the loaded portions of the pipeline subside more deeply than the unloaded portions, with the observed settlement difference reaching up to 100 mm.

V. CONCLUSION

Consolidation performance. The vacuum-assisted PVD scheme met the consolidation targets efficiently. With PVD spacing 1.5 m, drains to 22 m, a 50 kPa vacuum, and a 4 m embankment placed in four 1 m stages, the ground reached $\sim 90\%$ consolidation by the end of the final dwell, with total settlement ≈ 3.10 m and a ~ 30 -day terminal dwell. Time-history records show rapid excess pore-pressure dissipation followed by a low, steady settlement rate, indicating the foundation is sufficiently stabilized to proceed to upper-structure works without extending the preloading period.

Pipeline response and safety. The integrated soil–pipeline analysis yields peak actions of 12.86 kN·m/m (bending), 115.4 kN/m (shear), and 2,884 kN/m (axial). The governing computed stress is 381 MPa, which is below the allowable 435 MPa (\approx 63 ksi), giving a minimum safety factor \approx 1.1 even under the degraded wall-thickness scenario. Within the analyzed staging and vacuum level, the existing buried pipeline remains structurally safe, provided construction sequencing and vacuum delivery are maintained as designed and local curvature is monitored at critical stations.

Differential settlement and operational control. Non-uniform external loading along the alignment produces a differential settlement up to \sim 100 mm between loaded and lightly loaded segments. While acceptable for the current design envelope, this calls for continued staging control and instrumented monitoring (settlement plates and vibrating-wire piezometers) to limit curvature demand and to verify that residual Δu remains low. Practical go/no-go criteria should include a daily settlement rate threshold ($<$ 1–2 mm/day) and residual pore pressure reduced to a small fraction of the stage peak before advancing lifts.

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