JOS - MRK ***Volume 7, Nomor 1, Maret 2026, Page 292-297***

JURNAL ONLINE SKRIPSI
MANAJEMEN REKAYASA KONSTRUKSI POLINEMA

Journal homepage: http://jurnal.polinema.ac.id/ **ISSN: 2722-9203 (media online/daring)**

COMPARATIVE STUDY OF THEORETICAL AND FIELD DATA ON SOIL SETTLEMENT: PLAZA SUMMARECON BANDUNG CASE STUDY

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ABSTRACT

This research investigates the discrepancy between theoretical and actual field settlement in soft clay soils, using the Plaza Summarecon Bandung project as a case study. Soil improvement techniques involving preloading and the installation of Prefabricated Vertical Drains (PVD) and Prefabricated Horizontal Drains (PHD) were applied to accelerate consolidation and enhance soil stability. The objective of this study is to compare theoretical settlement calculations with actual field measurements, identify contributing factors to discrepancies, and propose refinements to the theoretical models. The research method involves collecting soil investigation data, field monitoring data (Settlement Plates), and project construction documentation. Theoretical settlement was calculated using Terzaghi's one-dimensional consolidation theory and extended with Barron and Hansbo's PVD acceleration models. Field settlement data were analyzed over time to create settlement curves and evaluate actual behavior during the preloading period. Findings show that actual settlement significantly deviates from theoretical predictions. The settlement prediction accuracy for Settlement Plate (SP) 1 is 25.43%, SP-2 is 46.97%, and SP-3 is 94.40%. The deviation is primarily due to incomplete soil investigation data, omission of construction and indirect loads in theoretical models, and inconsistencies in field monitoring. Additionally, differences in PVD patterns (triangular vs. square) affected the time to 90% consolidation, with triangular layouts achieving faster results due to better service area coverage. This study concludes that theoretical models can be refined by incorporating site-specific factors, adhering to standard soil investigation protocols, and improving field monitoring practices. It emphasizes the importance of accurate modeling and continuous instrumentation for ensuring reliable ground improvement in soft soil areas.

***Keywords** : soil settlement; prefabricated vertical drain (PVD); consolidation; field monitoring; geotechnical engineering*

1. BACKGROUND

Building a foundation is a common practice and one of the most important steps in constructing any infrastructure or building within human civilization. A well-designed foundation ensures the stability and durability of structures, supporting the loads imposed on them. However, choosing a suitable type of foundation requires a careful consideration of various factors, including the height and width of the structure. One of the most significant factors influencing foundation design is the soil condition, which varies across different locations with distinct characteristics.

Clay soil absorbs more water, causing its particles to expand, and when it dries, it shrinks like concrete. The presence of excessive water within clay soil is preventing us to build a building without compromising our soil bearing capacity, which is important in foundation stability. Because of clay soil's high water retention, it has low bearing capacity and could compromise structural integrity, leading to potential failures. Therefore, soil improvement techniques must be applied to strengthen the bearing capacity and stability of clay soil before construction begins.

One of the effective soil improvement methods for clay soil is consolidation through drainage. Consolidation is a process that gradually reduces soil volume by expelling water under sustained load, thereby increasing soil strength and stability. However, natural consolidation is a slow process, often taking years to complete. To accelerate consolidation, engineered solutions such as vertical and horizontal drainage systems are implemented. Among these solutions, geotextiles have an important role in soft soil consolidation.

Geotextiles are permeable fabric materials used in geotechnical applications to improve soil properties, including drainage, filtration, and reinforcement. Specifically, for drainage purposes, Prefabricated Vertical and Horizontal Drains (PVD and PHD) are employed to expedite the removal of excess water from clay soil, thereby accelerating consolidation and improving soil strength.

The settlement values in the Plaza Summarecon Bandung calculated through theoretical settlement models did not match the actual field measurements. This discrepancy highlights a fundamental challenge in geotechnical engineering. The limited availability and accuracy of soil data often result in differences between theoretical settlement estimations and observed field results. Consequently, this thesis aims to analyze settlement data obtained from field measurements using Settlement Plates (SP) and compare them with theoretical predictions to assess their accuracy and reliability.

The comparative analysis of soil settlement predictions using theoretical calculations and field data in this study stems from the observed inconsistencies between the two, highlighting the need for improved methodologies in geotechnical engineering.

2. METHOD

The following is the workflow diagram for research:

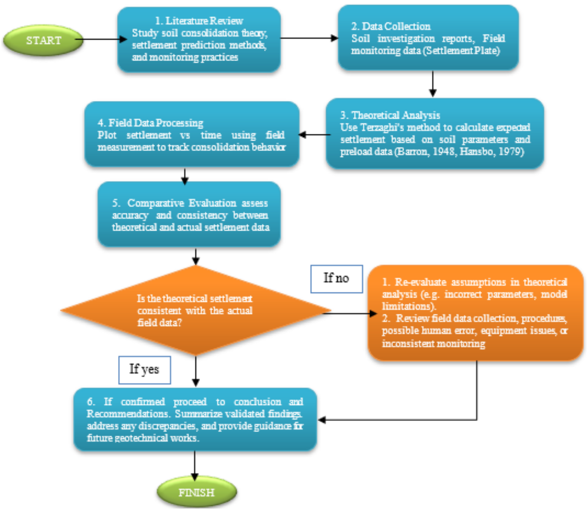

Figure 1: Flow Chart of the Research

3. RESULT AND DISCUSSION

Here is the analysis of the research:

3.1 Borehole data

Table 1: Borehole Data 1

Borehole	Depth (m)	Soil Particle Analysis Test (%)				Soil Classification
		Gravel	Sand	Silt	Clay	
BH-01	1,5-2	0.00	0.28	35.96	63.76	CH
	7,5-8	0.00	0.36	45.36	54.28	CH
	13,5-14	0.00	0.00	31.23	68.77	CH
	19,5-20	0.00	1.59	48.17	50.24	MH
	25,5-26	0.00	0.49	45.24	54.27	CH
	43,5-44	0.00	0.00	38.98	61.02	CH
	49-50	0.00	0.80	19.02	80.18	CH
BH-02	5,5-6	0.00	3.32	39.98	56.70	CH
	13,5-14	0.00	0.48	41.55	57.97	CH
	17,5-18	0.00	4.45	42.46	53.09	CH
	25,5-26	0.00	0.95	40.60	58.45	CH
	43,5-44	0.00	0.49	30.43	69.08	CH
	51,5-52	0.00	1.44	12.77	85.79	CH
	57,5-58	0.00	4.03	42.05	53.92	CH
BH-03	5,5-6	0.00	0.89	43.79	55.32	CH
	9,5-10	0.00	0.00	46.64	53.36	CH
	17,5-18	0.00	1.20	29.83	68.97	CH
	21,5-22	0.00	0.00	45.72	54.28	CH
	27,5-28	0.00	0.00	40.57	59.43	CH
	35,5-36	0.00	0.00	48.65	51.35	CH
	45,5-46	0.00	0.00	25.59	74.41	CH

Table 2: Borehole Data 2

Bore hole	Depth (m)	Soil Consolidation Test			Test Volume			
		C_c	C_s	e_0	γ_{sat}	γ_{dry}	W_c	G_s
BH-01	1,5-2			1.91	1.43	0.83	72.39	2.41
	7,5-8			4.89	1.19	0.42	185.08	2.47
	13,5-14			3.22	1.36	0.58	132.96	2.46
	19,5-20	0.643	0.113	1.63	1.56	0.99	56.89	2.62
	25,5-26			5.01	1.16	0.41	182.22	2.46
	43,5-44			1.28	1.66	1.17	41.98	2.66
	49-50	0.344	0.095	1.32	1.65	1.16	42.50	2.68
BH-02	5,5-6			6.49	1.16	0.33	249.70	2.47
	13,5-14			3.81	1.31	0.52	152.84	2.49
	17,5-18			3.09	1.42	0.63	124.82	2.59
	25,5-26			5.42	1.21	0.39	212.06	2.49
	43,5-44	0.450	0.043	1.33	1.68	1.15	46.45	2.67
	51,5-52			1.17	1.72	1.24	38.97	2.69
	57,5-58	0.392	0.062	1.26	1.66	1.18	40.56	2.68
BH-03	5,5-6			5.92	1.16	0.35	229.50	2.44
	9,5-10			6.67	1.12	0.32	246.54	2.47
	17,5-18			3.66	1.36	0.52	158.26	2.45
	21,5-22	1.250	0.118	3.84	1.27	0.54	136.27	2.59
	27,5-28			3.81	1.31	0.53	144.93	2.57
	35,5-36			2.90	1.35	0.66	103.46	2.59
	45,5-46	0.426	0.100	1.37	1.66	1.13	47.14	2.68

Table 3: Borehole Data 3

Borehole	Depth (m)	Atterberg Limit			Triaxial Test	
		LL	PL	PI	c' (kg/cm²)	φ' (°)
BH-01	1,5-2	79.97	26.93	53.03	0.24	29.20
	7,5-8	190.64	42.32	148.31	0.09	27.10
	13,5-14	148.73	27.08	121.65	0.11	1.70
	19,5-20	60.74	32.91	27.83	0.49	0.80
	25,5-26	207.72	48.47	159.25	0.11	1.60
	43,5-44	81.23	27.75	53.48	2.28	3.30
	49-50	96.64	27.08	69.57	-	-
BH-02	5,5-6	302.54	42.92	259.62	0.16	26.10
	13,5-14	157.80	37.48	120.32	0.08	2.00
	17,5-18	132.54	30.17	102.37	0.12	2.80
	25,5-26	283.62	71.21	212.41	0.32	1.70
	43,5-44	75.85	32.07	43.78	1.01	3.80
	51,5-52	96.51	25.24	71.27	-	-
	57,5-58	72.52	25.36	47.17	-	-
BH-03	5,5-6	232.83	42.70	190.12	0.12	26.50
	9,5-10	270.71	73.07	197.68	0.20	26.10
	17,5-18	166.01	47.61	118.41	0.11	0.70
	21,5-22	149.03	42.11	106.92	0.96	4.70
	27,5-28	165.09	28.41	136.68	0.77	2.10
	35,5-36	120.34	47.02	73.33	-	-

	45,5-46	90.15	30.06	60.09	-	-

According to the borehole data, we could see that the void ratio and liquid limit of borehole 3 are relatively bigger than the void ratio and liquid limit on borehole 1 and 2. Therefore it means that the soil in the borehole 3 area might be worse than the soil on borehole 1 and 2 in the area of settlement plate 1. This might mean the area around settlement plate 2 and 3 could have a different soil properties and the uncertainty of the properties could cause inaccurate estimation of soil settlement around the area. From the borehole data, here is the soil parameter that will be used in the calculation.

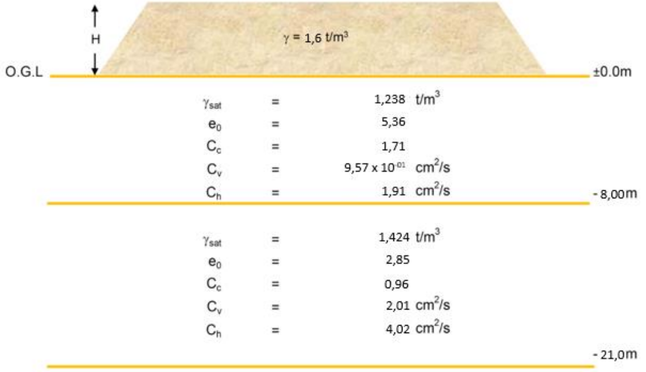

Figure 2 : Soil Profile Parameters

3.2 Stage of Preloading Load Calculation

a. Soil Preloading Height Design

1. Determine a specific constant value for qfinal , for example : q = 1 ton/m2.
2. With the assumed qfinal and the desired embankment shape, calculate the consolidation settlement, for example, resulting in = Sci.
3. Determine Hinitial and Hfinal resulting from the selected q.
4. Repeat the steps above for qfinal = 3 ton/m2; 5 ton/m2; 7 ton/m2; 10 ton/m2; etc. Also determine the corresponding values of Sc, Hinitial, dan Hfinal.
5. Create a table containing qfinal i, Sci, Hinitial i, dan Hfinal i.
6. Create a graph showing the relationship between Hinitial and Hfinal (Hbeginning= Hinitial = Happlicated = Hplan ; Hlast = Hfinal). Also create a graph showing the relationship between settlement (Sc) and Hinitial.
7. From the graph of Hinitial and Hfinal, determine the required Hinitial for a given Hfinal.

From these stages, here is the soil preloading height calculation and the desired preloading can be estimated:

Table 4: Height Calculation

Load (q) (t/m²)	Soil Settlement Sc (m)	Initial Height of Preloading (m)	Final Height of Preloading (m)
1	0.174326014	1	0.825673986
3	0.828323131	2	1.171676869
5	1.666381343	4	2.333618657
7	2.306146277	6	3.693853723
10	3.055336226	8	4.944663774
15	3.986123728	12	8.013876272
20	4.690376855	16	11.30962315

Table 5 : Desired Calculation for Soil Preloading

NO	DETAILS	UNIT	VALUE	ELEVATION
A	**DATA INPUT**			
1	Original ground elevation	m	662.0	662.0
2	γ soil preloading (A)	ton/m³	1.6	-
3	Service load/House load (B)	ton/m²	1.6	-
4	The service load is assumed to be equivalent to 1,0m soil embankment with a unit weight of (g) 1,6 ton/m³ (C)	m	1.000	665.1
5	Elevation design (D)	m	2.100	664.1
6	Final height of the soil preloading (E)	m	3.100	665.1
B	**DATA OUTPUT**			
1	Height application for soil preloading (graph) (F)	m	4.850	666.85
2	Total Settlement estimation (graph) (G)	m	1.750	-
3	Consolidation settlement at 90% (H)	m	1.575	-
4	Consolidation settlement at 60% (H)	m	1.050	-

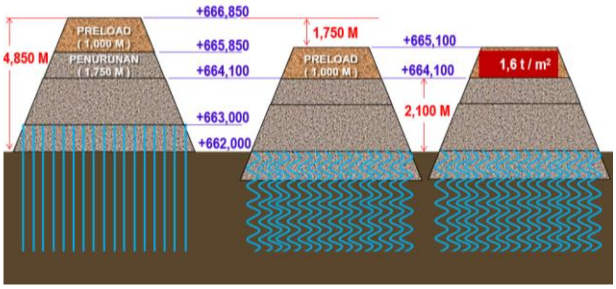

Figure 3 : Soil Embankment Work Scenario

3.3 Design of PVD

From the data, we are able to calculate consolidation with and without PVD.

Table 6 : Natural Consolidation without PVD

Year	T_v	a	U_v	Year	T_v	a	U_v
0	0.0000	-	0.0000	500	0.8280	1.0213	89.495
10	0.0165	-	14.5247	550	0.9108	0.9326	91.437
50	0.0828	-	32.4784	600	0.9936	0.8438	93.019
100	0.1656	-	45.9314	650	1.0764	0.7551	94.309
150	0.2484	-	56.2542	700	1.1592	0.6663	95.361
200	0.3312	1.5538	64.1995	750	1.2420	0.5776	96.218
250	0.4140	1.4651	70.8165	800	1.3248	0.4888	96.917
300	0.4968	1.3763	76.2105	850	1.4076	0.4001	97.487
350	0.5796	1.2876	80.6075	900	1.4905	0.3113	97.951
400	0.6624	1.1988	84.1918	950	1.5733	0.2226	98.330
450	0.7452	1.1101	87.1136	1000	1.6561	0.1338	98.639

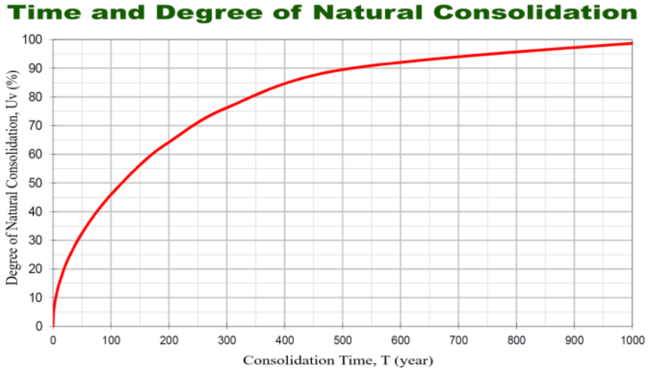

Figure 4: Time and Degree of Natural Consolidation

Here is of the summary of PVD calculation with triangle pattern.

(PVD 4mm x 100mm; Triangle Pattern; Depth 27,0 m)

Table 7: Summary of PVD with Different Distance (s)

No	PVD Spacing s (m)	Time t (month)	Degree of Consolidation U_{av} (%)
1	1.0	3.50	90.00
2	1.1	4.50	90.00
3	1.2	5.75	90.00
4	1.3	6.75	90.00
5	1.4	8.00	90.00
6	1.5	9.50	90.00

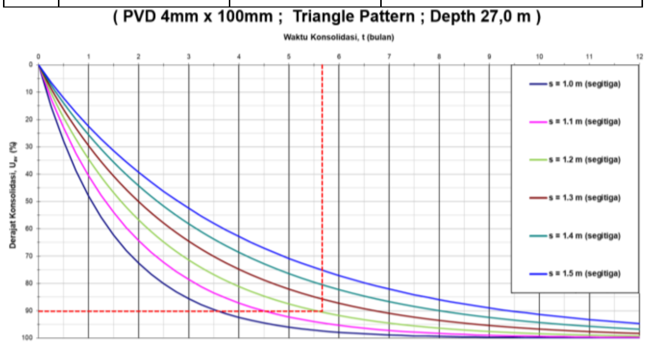

Figure 5: Graph of Triangle Pattern PVD using difference distance (s)

Here is of the summary of PVD calculation with square pattern.

(PVD 4mm x 100mm; Square Pattern; Depth 27,0 m)

Table 8: Square Pattern Acceleration Consolidation with PVD

No	PVD Spacing s (m)	Time t (month)	Degree of Consolidation U_{av} (%)
1	1.0	4.25	90.00
2	1.1	5.50	90.00
3	1.2	6.75	90.00
4	1.3	8.00	90.00
5	1.4	9.50	90.00
6	1.5	11.25	90.00

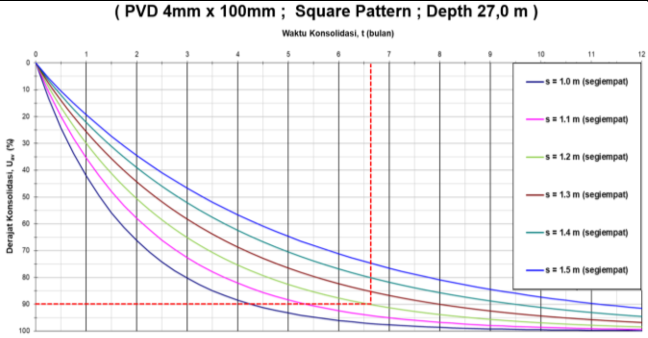

Figure 6: Graph of Square Pattern PVD using difference distance (s)

3.4 Design of PHD

By completing the calculation for PVD, we are able to continue to determine the calculation of PHD as the next water waste distributor.

The amount of soil settlement at 90% = 1,575 m.

Consolidation time at 90% = 5,75 months.

Discharge = 1,0568 x 10^{-7} m^3/s

The amount of soil settlement at 60% = 1,050 m.

Consolidation time at 60% = 2,25 months.

Discharge = 6,9102 x 10^{-7} m^3/s

For triangle pattern PVD installation with 1,2 m spacing:

Service area of 1 PVD point = Ae = 1,246 m^2

The discharges a vertical water volume of : 8,6163 x 10^{-7} m^3/s

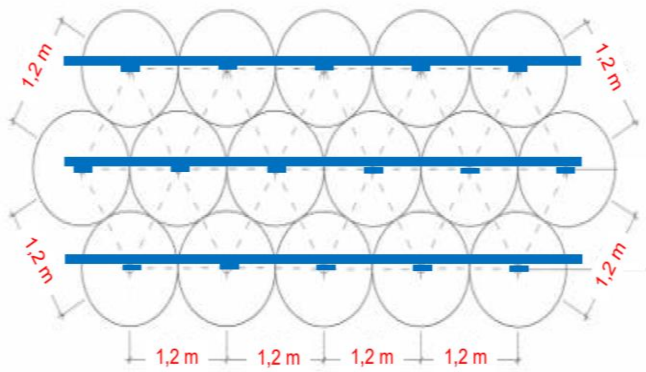

Figure 7: Installation of PHD at PVD points

Maximum length on 1 lane PHD = 27 meter

= 23 points of PVD

Maximum water discharge on 1 lane PHD = 1,9817 x 10^{-5} m^3/s

Properties	Test Method	Unit	CT-SD100-20	CT-SD100-30
Composite Drain				
Width	Nominal	mm	100	100
Thickness	ASTM D 5199	mm	20	30
Horizontal Permeability	ASTM D 4491	m/s	0.15	0.15
Discharge Capacity @1%	ASTM D 4716	m^3/s	$2.4*10^{-4}$	$3.6*10^{-4}$
Compressive Strength	ASTM D 1621	kN/m^2	600	600
Core				
Profile	-	-	Cuspated	Cuspated
Color	-	-	Black	Black
Material	-	-	HDPE	HDPE
Filter				
Material	-	-	PET	PET
UV Stabilized	-	-	yes	yes
Grab Strength	ASTM D 4632	N	>450	>450
Permeability	ASTM D 4491	m/s	$1.5*10^{-4}$	$1.5*10^{-4}$
Mass per Unit Area	ASTM D 4595	g/m^2	180	180

Figure 8: PHD CT-SD100-20

Flow Capacity of PHD CT-SD100-20 = 2,4 x 10^{-4} m^3/sec

Flow Discharge PHD needed = 1.9817 x 10^{-5} m^3/sec

3.5 Actual Data Analysis

With the existing field data, we should make a graph about the settlement for each settlement plate and make a comparosion with theoretical settlement.

- Settlement Plate 1

Based on the comparison, Settlement plate 1 is a lot bigger than the theoretical settlement. On the first day the settlement went as big as 521mm then it went normally the next day. on 06th September 2017 the theoretical settlement number nearly hits 2000mm while the actual hits 3114mm.

- Settlement Plate 2

Based on the comparison, the actual settlement started bigger than theoretical data. On the first day at 1st April 2017 the settlement went as big as 420mm, then on 29th April 2017 it went smaller and had the same settlement as the theoretical data and it went similarly accurate until 27th may 2017 and after that it went bigger and far bigger than the theoretical settlement prediction. By the end of the regular monitoring at 6th September 2017 the total settlement measured by Settlement Plate (SP) 2 is 2748mm and is significantly bigger than the theoretical settlement.

- Settlement Plate 3

Based on the comparison, the actual settlement started bigger than theoretical data, the settlement occurred on the first day on the 1st April 2017 is 155mm then on 12th April 2017 it went smaller and had the same settlement as the theoretical data and it went far smaller until 6th September 2017 where the settlement went similarly accurate with the theoretical data.

Table 9: Monitoring data 1 year after the settlement reach 90%

NO	SP CODE	GROUND SOIL ELEVATION (m)	PRELOADING ELEVATION (m)	PRELOADING HEIGHT (m)	TOTAL SETTLEMENT (mm)	EXPLANATION
A	B	C	D	E (D-C)	F	G
1	SP 01	658.804	664.401	5.597	-3326	Top Preload
2	SP 02	659.231	664.393	5.162	-2963	Top Preload
3	SP 03	660.105	665.159	5.054	-2147	Top Preload

Table 10: Plan Comparison and Realization

NO	DETAILS	PLAN	REALIZATION
1	PVD Installation Pattern	Triangle	Triangle
2	Spacing of PVD Installation	1,2 m	1,2 m
3	Depth of PVD Installation	28,000 m	27,79 m
4	Executed Embankment Height	4,850 m	5,683 m 5,027 m 5,071 m
5	Settlement (90%)	1,575 m	3,055 m 2,678 m 1,848 m
6	Consolidation waiting time (90%)	5,75 months	66 + 77 days 65 + 77 days 76 +67 days

Table 11: Settlement Fulfilled per Week

T (Week)	Estimated Sc (mm)	SP-01		SP-02		SP-03	
		Settlement	Fullfilled	Settlement	Fullfilled	Settlement	Fullfilled
1	-206	-1175	100%	-697	100%	-203	99%
2	-422	-1269	100%	-770	100%	-233	55%
3	-530	-1321	100%	-805	100%	-249	47%
4	-639	-1449	100%	-876	100%	-272	43%
5	-730	-1546	100%	-939	100%	-308	42%
6	-822	-1670	100%	-1025	100%	-344	42%
7	-906	-1831	100%	-1176	100%	-422	47%
8	-988	-2006	100%	-1376	100%	-589	60%
9	-1063	-2208	100%	-1567	100%	-760	72%
10	-1137	-2359	100%	-1754	100%	-894	79%
11	-1206	-2515	100%	-1925	100%	-1042	86%
12	1268	-2624	100%	-2078	100%	-1197	94%
13	-1317	-2700	100%	-2191	100%	-1322	100%
14	-1367	-2772	100%	-2293	100%	-1437	100%
15	-1405	-2826	100%	-2374	100%	-1525	100%
16	-1435	-2881	100%	-2446	100%	-1599	100%
17	-1463	-2930	100%	-2509	100%	-1666	100%
18	-1496	-2972	100%	-2568	100%	-1729	100%
19	-1514	-3006	100%	-2616	100%	-1784	100%

20	-1534	-3044	100%	-2663	100%	-1833	100%
21	-1553	-3072	100%	-2698	100%	-1869	100%
22	-1569	-3092	100%	-2723	100%	-1894	100%
23	-1579	-3123	100%	-2756	100%	-1925	100%
	Accuracy Average		100%		100%		100%

Then we measure the accuracy of the estimated settlement with the actual settlement on the field using relative error formula.

Settlement measured on SP-1 =-3,055m

Settlement measured on SP-2 =-2,678m

Settlement measured on SP-3 =-1,848m

While the target of estimation is -1,750m

With that the Accuracy of Settlement on

SP-1=25,43%

SP-2=46,97%

SP-3=94,40%

4. CONCLUSION

This research intended to evaluate the comparison between theoretical settlement predictions and actual field measurements at the Plaza Summarecon Bandung site, also to investigate the primary factors contributing to any discrepancies, and provide insight into how theoretical models can be refined to increase prediction accuracy. Here is the conclusion for each problem statement:

1) Theoretical settlement predictions generally underestimated actual field measurements. For example, SP-1 settled -3.055 m, while the theoretical value was -1.750 m, showing up to 74% deviation. The closest match was at SP-3 (94.40% accuracy), indicating variations depending on site load conditions.
2) The main factors include: Limited and non-uniform borehole data, Exclusion of dynamic and construction loads, Indirect load effects due to gradual preloading, Inconsistent field monitoring and weather influences, and Neglecting resistance factors of soil and PVD.
3) Accuracy can be improved by: Ensuring adequate soil investigation per standards, Considering indirect, dynamic, and construction loads, Applying real-time monitoring instruments, and Including resistance factors (Fs and Fr) in calculations.

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