Consolidation settlement prediction and monitoring of toll road embankment at STA 23+650 Semarang–Demak Toll Road section

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Abstract. The development of toll road projects in Indonesia is experiencing rapid growth. However, due to the large number of toll roads being constructed over soft soil areas, it is crucial to address the issue of consolidation settlement. This is because settlement can lead to differential or excessive settlement, which potentially damages the structures built on such soil. Unfortunately, consolidation settlement on soft soils is a time-consuming process. Thus, a consolidation acceleration method is needed, one of which is to use a combination of PVD–Preloading. This method can also increase the soil's bearing capacity, thereby contributing to the preservation and protection of systems that support human activities while maintaining a balance with nature. Therefore, this study aims to investigate consolidation settlement employing PVD–Preloading methods. The analysis focused on a case study conducted at STA 23+650 of the Semarang-Demak Toll Road section. The analysis employed the Asaoka method, integrating field monitoring instruments, along with the Terzaghi method for one-dimensional consolidation. The results showed that the settlement results from the Asaoka and Terzaghi methods correlate with the settlement plate instrumentation in the field.

1 Introduction

The main role of soil in building construction is to support the load and the construction materials on it. Therefore, the soil must have sufficient bearing capacity to support the load due to the structures built on it. When soft soil is used as a subgrade or foundation in construction, this can pose a problem due to its inherent characteristics. Soft soil is characterized by high compressibility, high saturation level, low undrained resistance, and low shear resistance [1]. Due to these soft soil characteristics, it is necessary to ensure the safety and stability of the structures built on such soil [2]. One significant issue that arises is consolidation settlement in soft soils, which can lead to differential or excessive settlement of the structures.

Consolidation settlement occurs when water-saturated soil undergoes volume changes due to the discharge of water from its pores [2]. Due to the small permeability of soft soil, consolidation settlement may take a long time to complete, possibly longer than the intended lifespan of the structures. Consolidation theory is needed to predict the magnitude and velocity of consolidation settlement to ensure the serviceability of structures built on compressible soil layers. Based on this, it is necessary to improve the soil to reduce the consolidation time, for instance by employing Preloading and Pre-fabricated Vertical Drain (PVD) methods [3, 4]. These methods aim to accelerate settlement by reducing the water and air content in soil particles, thus accelerating consolidation settlement.

The application of Preloading and PVD for soil improvement has been successfully demonstrated in the North Surabaya area, which features sea clay soil. The results show a highly effective acceleration of consolidation, with the settlement rate of clay employing PVD and preloading twice as fast as that of embankments without PVD after 280 days [5]. Moreover, vertical drainage with preloading has proven to be highly effective in improving the sub-grade runway of *Tempuling* Airport, achieving a 40-times acceleration in the planned settlement [6].

There are several methods for calculating consolidation settlement. One of them is by using Terzaghi's (1943) one-dimensional consolidation theory, which has been employed to predict settlement and consolidation time. This method calculates the consolidation settlement based on the soil parameters tested in the laboratory. However, in many cases, the consolidation settlement estimated by Terzaghi theory differs slightly from the actual settlement in the field. The inaccuracy is caused by neglecting several factors related to the stockpiling method. Another procedure for analysing consolidation settlement is based on field observations, also known as Asaoka Method [7]. This procedure can predict the actual settlement without requiring the soil parameters used in Terzaghi's 1-dimensional consolidation analysis. The Asaoka prediction involves compiling and analysing actual

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settlement data from the field using the Settlement Plate instrumentation and then applying the curve fitting method to analyse the settlement.

The Semarang-Demak Toll Road project aims to reduce congestion in the north coast area. Additionally, The northern part of Semarang is prone to tidal flooding, which further increases traffic density. The increase in vehicle accumulation leads to higher traffic saturation along the north coast of Semarang. However, the Semarang-Demak Toll Road construction faces a challenge due to may undergo potential consolidation settlement in soft soil. Therefore, this study investigated consolidation settlement in a case study at STA 23+650 of the Semarang-Demak Toll Road section. This study employed observation monitoring by using settlement plate instrumentation, Asaoka's prediction method, and Terzaghi's one-dimensional method. Based on this analysis, it is expected to determine how the results of the settlement and what parameter factors may affect the settlement.

2 Method

This study focused on a case study on Semarang–Demak Toll Road section, precisely at STA 23+650. The Semarang-Demak Toll Road section from STA 10+690 to STA 27+000 is mostly surrounded by paddy fields and ponds. An overview of the study can be seen in Fig. 1. Fig. 1 shows that there are rice fields and trees on either side of the toll road, with very few buildings. There are several buildings, but with a limited number and the location is relatively far from the Semarang–Demak Toll Road section. Therefore, it can be considered that other buildings nearby have little impact on the stability of the toll road construction.

Fig. 1. Aerial photography with a drone on Semarang–Demak Toll Road section (PT PP).

The toll road construction in this area is challenging because of the soft soil type that serves as a subgrade of the toll road. Iqbal et al. (2020) stated that an increase in dryland farming (coffee-based agriculture), paddy fields, and buildings can be a cause of soil quality problems such as erosion and soil cracks [8]. Based on Standard Penetration Test (SPT) and Cone Penetration Test (CPT), the stratification of soil at this STA is presented in Fig. 2. The soil types at STA 23+650 range from soft clay to stiff clay, and some contain silt and sandy clay. The SPT value is quite low from 2 to 50 at a depth of 36 meters, while the conus resistance (qc) value of the CPT ranges from 0.6 MPa to 2.4 MPa at a depth of up to 30 meters.

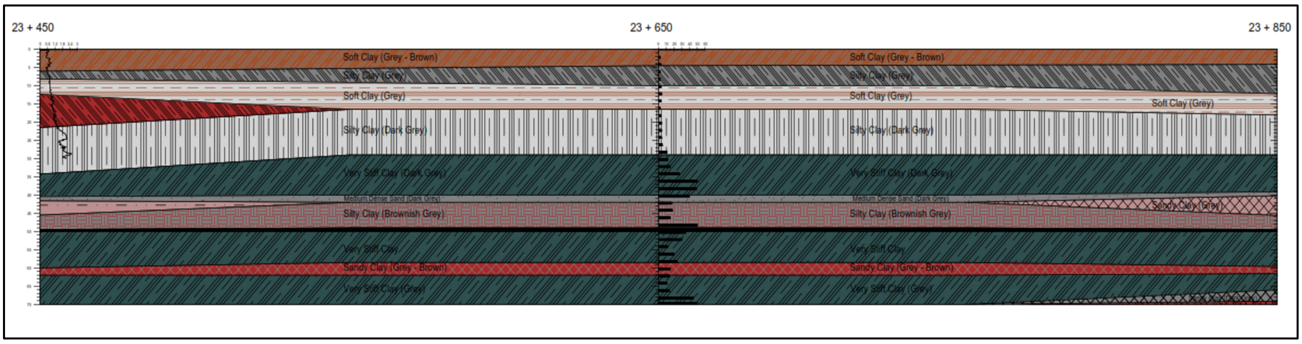

Fig. 2. Stratification of soil at STA 23+650 of the Semarang–Demak Toll Road section

To accelerate the consolidation process, the PVD–Preloading method was employed at STA 23+650 of the Semarang-Demak Toll Road section. The PVD design employed a triangular pattern with a width of 100 mm, a depth of 22 m, and a spacing of 0.9 m. The PVD installation pattern can be seen in Fig. 3.

The construction of Toll Road involves the construction of embankments. Beneath the embankment, there are geotechnical instrumentation, settlement plates, inclinometers, and piezometers. These instrumentations were used to monitor and evaluate during the consolidation process.

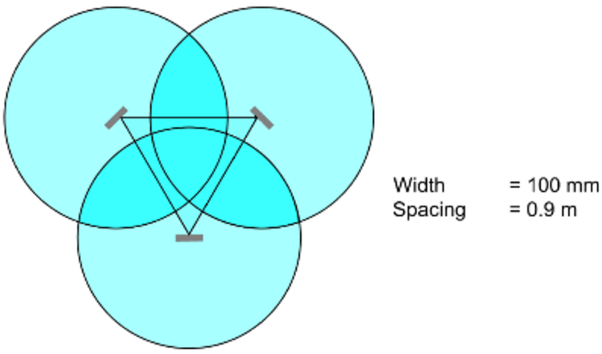

Fig. 3. Triangular PVD installation pattern.

The embankment has a slope ratio of V:H = 1:1. Fig. 4 shows more details of the cross-section of the toll road with accelerated consolidation employing the PVD-Preloading method. The embankment provides loading to accelerate consolidation settlement by PVD. Upon completion of the embankment construction, temporary preloading is employed to further enhance consolidation. Therefore, the loads on the embankment with preloading were designed to achieve a degree of consolidation of 90%. These embankment and preloading materials share the same material specifications with a dry unit weight of 1.56 gr/cm^3 and an OMC of 17.78%.

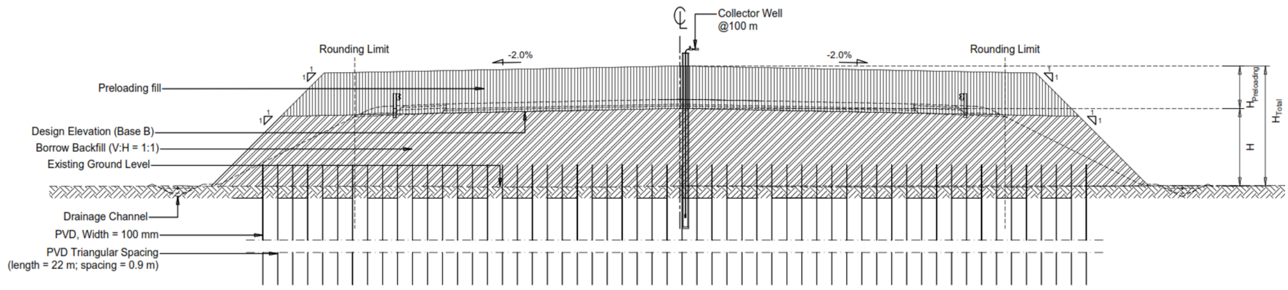

Fig. 4. Typical cross section and preloading design.

During the preloading work, a settlement plate instrumentation was employed to monitor consolidation settlement. Based on this settlement plate, it is possible to evaluate consolidation settlement (total settlement and time to reach it) employing Asaoka method. Asaoka method is a curve fitting method for predicting consolidation settlement. This method does not require soil data parameters but still produces reliable results. The Asaoka method has been proven reliable for estimating field settlement [9] and can be applied with or without a vertical drain [10]. The steps for predicting consolidation settlement using the Asaoka method are:

1. Recap the data obtained from the monitoring geotechnical instruments, particularly settlement plates, on the repaired soil area.
2. Determine the data recap interval of at least 3 days.
3. Select the relevant data for plotting, starting from the stable settlement to the final settlement.
4. Plot the graphs ρk (y-axis) vs ρk-1 (x-axis) from the selected data (Fig. 5).
5. Draw a line at 45^0 on the graph as in Fig. 5.

Fig. 6 shows settlement data that have been plotted, resulting in final settlement at the initial stage of embankment and that at the end of preloading embankment.

Furthermore, in this study, an analysis was carried out using the Terzaghi 's one-dimensional consolidation method. Normally, consolidated clay soil can be calculated using Equation 1 [11]. The soil parameter values employed are derived from field tests and laboratory tests, which are correlated with the soil types based on existing literature studies.

$$Sc = \left(\frac{C_c x H_c}{1 + e_0}\right) log\left(\frac{\sigma'_0 + \Delta\sigma}{\sigma'_0}\right) \qquad (1)$$

Meanwhile, the height of preloading used in this study is based on existing field data from the settlement plate monitoring. The settlement results were monitored using a settlement plate and the monitoring date were plotted in a graph and then an analysis of the embankment stages used was carried out.

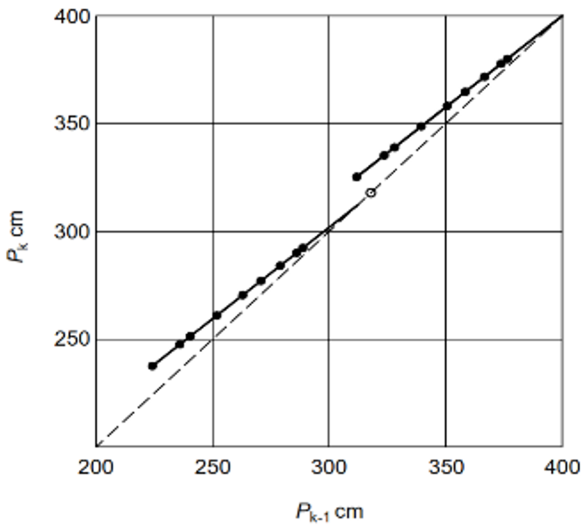

Fig. 5. Graphical method for predicting settlement with Asaoka Method (ρ_{k-1} vs ρ_k) [7].

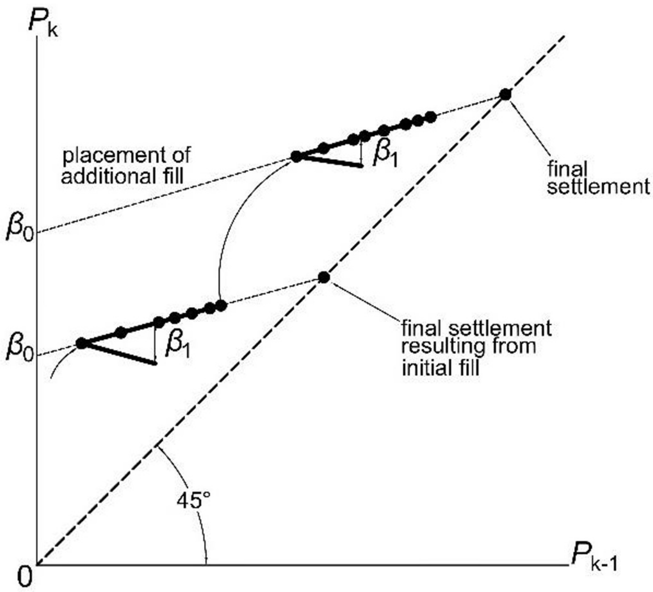

Fig. 6. Graphical method for predicting settlement with Asaoka Method (ρ_{k-1} vs ρ_k) [7].

3 Results and discussion

Based on observations from settlement plate instrumentation, STA 23 + 650 underwent 8 stages of embankment (Ht) as outlined in Table 1. The initial stage of preloading began on September 10^{th}, 2021 with an initial embankment height of 2.00 m. The final stage, preloading (heap stage 8), was completed on July 29^{th}, 2022 with an embankment height of 5.37 m. Plotting of embankment height and date at each stage of the embankment that occurred are illustrated in Fig. 7.

Furthermore, the settlement that occurred was also calculated employing the Terzaghi's one-dimensional (1D) method. In this study, it was determined that the depth of soft soil is 28 meters with NSPT value of 11, indicating a type of soft clay soil. This is due to the fact that at a depth of 29 meters, the soil transitions to a stiff clay type with an NSPT value higher than 12. The volume weight of the embankment is 15.6 kN/m^3. Meanwhile, the soil parameter data at an average depth of 0–20 meters shows a specific gravity of 2.65 and a void ratio of 1.65 (e_0). The coefficient of compressibility (Cc) is determined from the average values at a depth of 10-20 meters according to the availability of laboratory testing data, which is equal to 0.441. The calculation of consolidation settlement by preloading employing the Terzaghi's one-dimensional method is presented in Table 2.

Table 1. Stages of preloading embankment at STA 23+650 of the Semarang–Demak Toll Road section.

Stage	Preloading Embankment		Embankment Height (m)
	Start date	End date	H_t (m)
Stage 1	10/09/2021	01/10/2021	2.00
Stage 2	01/10/2021	21/10/2021	2.40
Stage 3	21/10/2021	04-Nov-21	3.16
Stage 4	04-Nov-21	11-Nov-21	3.42
Stage 5	11-Nov-21	16-Dec-21	3.71
Stage 6	16-Dec-21	30-Dec-21	4.25
Stage 7	30-Dec-21	20-Jan-22	4.95
Stage 8	20-Jan-22	29-Jul-22	5.37

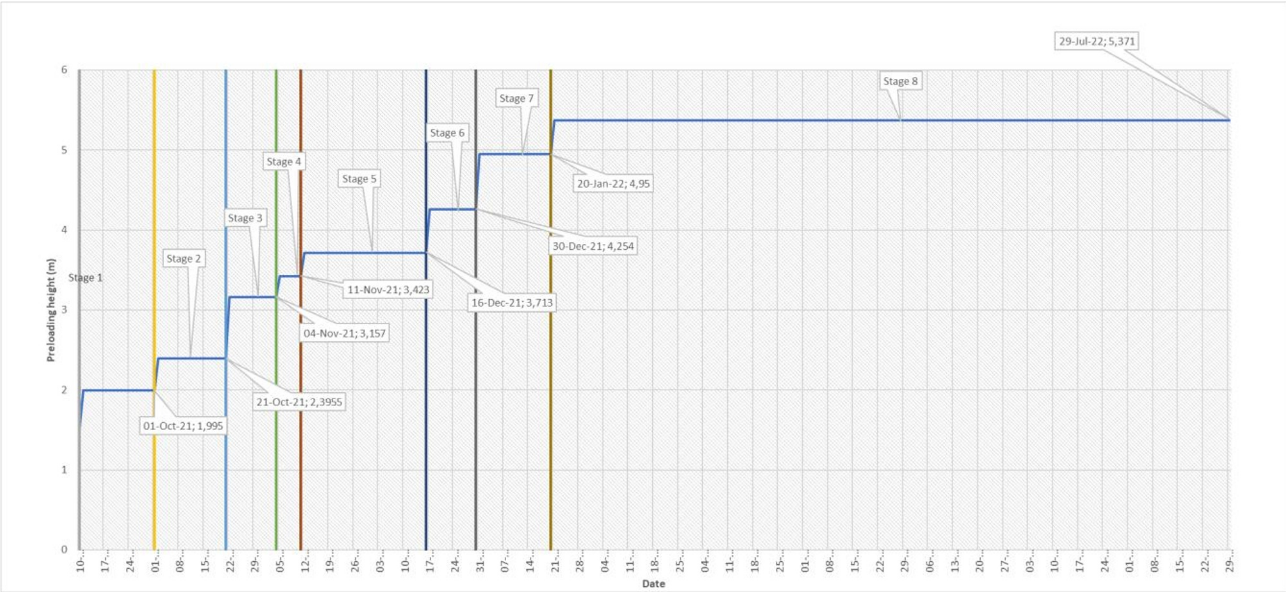

Fig. 7. The preload fill height of STA 23 + 650 of the Semarang Demak Toll Road section.

Table 2 shows that the settlement occurring at the 8^{th} stage of loading, which amounts to 1.30 m for 100% degree of consolidation and 1.17 m for 90% degree of consolidation. Furthermore, this settlement value was used to calculate settlement with a combination of preloading and PVD methods.

Based on laboratory test data, the coefficient of consolidation (Cv) value in the vertical direction is 0.000576 cm^2/s at a depth of 9.5–10 meters and 0.000691 cm^2/s at a depth of 19.5–20 meters, so that the obtained value of combined Cv is 0.00062958 cm^2/s or 0.038077019 m^2/week. The depth of PVD used is 22 meters with a width of 0.1 meters and a thickness of 0.003 meters. Furthermore, it is determined that the ratio of the horizontal and vertical permeability coefficients is 3. The PVD parameters used in the calculations in this case study are listed in Table 3.

The results of the calculations employing PVD can be seen in Table 4. Table 4 shows that the degree of consolidation of 95% is reached at an approximate settlement of 1.25 m and that of 100% is achieved at a settlement of 1.29 m. In this study, the consolidation settlement analysis for preloading–PVD methods was carried out directly at all stages to obtain the total consolidation settlement at the end of the period.

The Asaoka method was employed to predict settlements based on Curve fitting method on the existing settlement plate instrumentation monitoring observations. The settlement data obtained employing the Asaoka method are summarized in Table 5. According to Table 5, the largest deviation occurred at the initial stage (48.7%) and the smallest deviation occurred at the final stage (0.4%).

Table 2. Consolidation calculations Employing Terzaghi Preloading Method.

Load stages	Ht	q_0	Hclay	σ'_0	Stress Due to Preloading						Sc	
					B1	B2	z	α_1	α_2	$\Delta\sigma$	Sc (U=100%)	Sc (U=90%)
	m	kN/m	m	kN/m^2	m	m	m			kN/m^2		
1	2,00	31,20	28,00	85,45	23,00	2,00	14,00	0,04	1,02	29,35	0,60	0,54
2	2,40	37,44	27,40	83,63	22,60	2,40	13,70	0,04	1,03	35,29	0,70	0,63
3	3,16	49,30	27,30	83,32	21,84	3,16	13,65	0,06	1,01	46,37	0,87	0,79
4	3,42	53,35	27,13	82,79	21,58	3,42	13,56	0,06	1,01	50,19	0,93	0,84
5	3,71	57,88	27,07	82,62	21,29	3,71	13,54	0,07	1,00	54,41	0,99	0,89
6	4,25	66,30	27,01	82,43	20,75	4,25	13,51	0,08	0,99	62,23	1,10	0,99
7	4,95	77,22	26,90	82,10	20,05	4,95	13,45	0,10	0,98	72,33	1,23	1,10
8	5,37	83,77	26,77	81,70	19,63	5,37	13,39	0,11	0,97	78,39	1,30	1,17

Table 3. PVD parameters

Parameter	Value	Unit
Ch	0,114	
t	1,000	week
D	0,945	m
dw	0,066	m
n	14,412	
F (n)	1,926	
Tv	7,9E-05	
Uv	0,010	
Uv	1,001	%
Uh	0,412	
Uh	41,215	%
$U_{average}$	0,418	
$U_{average}$	41,804	%

Table 4. Calculation results of preloading – PVD

t (weeks)	Tv	Uv	Uh	Uaverage	Sc (m)
0	0	0	0	0	0
1	0,0001	0,0100	0,4122	41,80	0,54
2	0,0002	0,0142	0,6544	65,93	0,86
3	0,0002	0,0173	0,7969	80,04	1,04
4	0,0003	0,0200	0,8806	88,30	1,15
5	0,0004	0,0224	0,9298	93,14	1,21
6	0,0005	0,0245	0,9587	95,97	1,25
7	0,0006	0,0265	0,9757	97,64	1,27
8	0,0006	0,0283	0,9857	98,61	1,28
9	0,0007	0,0300	0,9916	99,19	1,29
10	0,0008	0,0316	0,9951	99,52	1,29

A comparative diagram of embankment height and settlement analysis employing settlement plates instrumentation monitoring, Asaoka predictions, and Terzaghi's One-Dimensional method is presented in Fig. 8. Fig. 8 reveals closely similar values between settlement plate observations, Asaoka prediction, and Terzaghi analysis methods. The settlement values for 100% degree of consolidation obtained from settlement plate observations, Asaoka predictions, and Terzaghi methods were recorded 1559 mm, 1552 mm and 1290 mm, respectively. Based on Fig. 8, the final settlement based on settlement gauge observations was 1559 mm on July 19th, 2022 with an embankment height of 5.371 m. Meanwhile, based on the Fig. 8, the settlement of 1.20 m, corresponding to 90% degree of consolidation, was observed on January 28th, 2022.

Table 5. Recapitulation of settlement prediction using Asaoka Method

Load stages	Preloading Height	High Ratio	Final Settlement Estimation (mm)		Deviation (%)
	H_t (m)	Hi/Ht	ρ_f (mm)	δ_n (mm)	
1	2,00	0,37	232,0	156	48,7
2	2,40	0,45	252,3	256	1,5
3	3,16	0,59	549,0	405	35,6
4	3,42	0,64	560,5	474	18,2
5	3,71	0,69	694,7	660	5,3
6	4,25	0,79	875,1	755	15,9
7	4,95	0,92	1210,9	1039	16,5
8	5,37	1,00	1552,9	1559	0,4

The findings of this study corroborate the study conducted by Benamghar and Boudjellal (2017), on a 15 m high embankment at PK245+000 of the railways under construction in Boughezoul-M'sila (Algeria), which employed the Terzaghi and Asaoka methods [12]. The settlement differences obtained employing the Terzaghi's 1-Dimensional method were larger compared to the Asaoka method, in relation to the field settlement plate observations. Moreover, the settlement results obtained from both methods were nearly identical, differing only by a few tenths of a millimeter. The difference is because Asaoka's method is theoretically based on Terzaghi's theory. However, the Asaoka method tends to generate more precise results based on the experimental observations compared to the empirical equation.

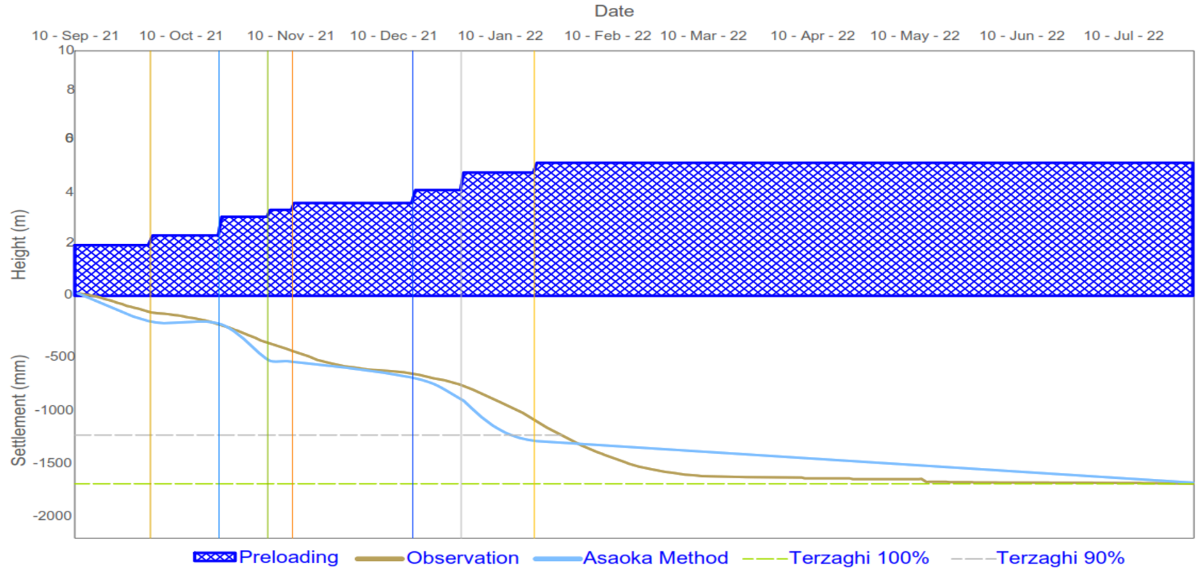

Fig. 8. Results of settlement analysis employing Settlement Plate Observations, Asaoka Method, and Terzaghi Method

Nevertheless, in this study, the settlement results obtained from the Terzaghi were lower than those from the Asaoka method. This is due to some uncertainties in the coefficients [7, 13], during the calculation process. As presented in Equation 1, parameters, such as the coefficient of compressibility (Cc) and void ratio (e_0) were involved. In addition, the parameter value for the coefficient of consolidation (Cv) is required for the settlement calculations employing PVD. It is important to note that these parameter values were obtained through laboratory testing which of course only took samples at several depths, whereas in this case study, sampling was taken at depths of 9.5–10 m and 19.5–20 m. These limited samples may not fully represent the soil condition from a depth of 0–22 meters (the PVD depth) as illustrated in Fig. 2, which consists of several soil layers. Therefore, accurate value determination of these soil parameters is crucial to ensure precise calculation of actual settlement in the field.

4 Conclusion

This study presents a comprehensive analysis of consolidation settlement through the integration of settlement plate instrumentation observations, Asaoka predictions, and the Terzaghi 1-Dimensional method. The findings reveal a close agreement between the final consolidation settlement determined from monitoring data (approximately 1559 mm) and the predictions employing the Asaoka and Terzaghi methods (1552 mm and 1290 mm). Thus, these methods in this study are effective to analyse consolidation settlement. Factors such as soil parameters in the Terzaghi method and the effect of changing parameters during the installation of Prefabricated Vertical Drains (PVD) in the field may affect the difference in consolidation settlement values.

However, further studies are required to develop the pattern of equations that accurately estimate settlement according to the existing soft soil types, considering the limitations of the Asaoka method in determining the initial line for settlement prediction, whereas the Terzaghi method requires complete soil parameter data for accurate analysis.

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