PREDICTION ANALYSIS ON COEFFICIENT OF CONSOLIDATION VALUES IN IMPROVED SOFT CLAYS

Eka Fitriana[1,2], Wimpie Agoeng Noegroho Aspar[3], Andri Arthono[4], Thiya Fiantika[3]

[1]Department of Civil Engineering, Mercu Buana University, Jakarta, Indonesia, 11650
[2]PT. Pandu Equator Prima, Bekasi, Indonesia, 17411
[3]National Research and Innovation Agency (BRIN), Indonesia
[4]Department of Civil Engineering, Al Kamal Science and Technology Institute (ISTA), Jakarta, Indonesia, 11520
e-mail : eka_nf@mercubuana.ac.id

ABSTRACT

Consolidation is a phenomenon in soil mechanics that often causes geotechnical problems. One solution to overcome consolidation phenomena is by speeding up process of pore water pressure dissipation. The type of soil improvement to upgrade the performance of soft clay is by applying pre-fabricated vertical drain (PVD) and pre-compression simultaneously. Geotechnical instrumentations such as settlement plates, piezometers, and inclinometers were installed at the field of study to monitor magnitude of settlement during consolidation process. After the final settlement was achieved, the consolidation parameters such as coefficient of consolidation, and rate of settlement, were back calculated. Prediction analysis of consolidations parameters was performed by means of Asaoka method. The results of this study is very interesting and provide useful engineering information. It is interesting to note that this case study may be beneficial use to practicing engineers and researchers.

Keywords: settlement; Asaoka method; degree of consolidation; geotechnical instrumentations; soft clay
Received: 2021-10-06; Revised: 2021-11-21; Accepted: 2021-12-03

INTRODUCTION

Consolidation is a phenomenon in soil mechanics that often causes geotechnical problems. Soil consolidation is an event of soil subsidence due to the dissipation of excess pore water for a long time. By giving a load on the soil, will cause an increase in the stress acting on the soil. The pore water will initially bear the additional stress acting on the soil due to the incompressible nature of water. This will cause excess pore water pressure. This excess pore water pressure will be dissipated by flowing out of the soil pore water through the soil pores. In contrast, the additional stress initially borne by the pore water is gradually transferred to the solid soil particles. This will result in a decrease in the volume of the soil, causing a settlement of consolidation.

The consolidation process will be faster by using the pre-compression method combined with installing a pre-fabricated vertical drain (PVD). PVD is an artificial drainage system that is installed vertically in a soft soil layer. This vertical drainage system has a shape in the form of a rectangular cross-sectional belt, consisting of a filter made of synthetic materials such as geotextiles, paper, or jute on the outside and an inside those functions as a water flow medium of plastic or organic fibres. The combination of this system aims to shorten the repair time for a thick layer of clay because the use of PVD will cause radial/horizontal pore water to flow which causes pore water pressure to be removed more quickly. The application of PVD is usually analysed using the finite element method to improve the performance of embankments on soft clay soils [1]. Furthermore, Basau et al. [2] performed an equal strain analysis in order to improve consolidation by considering the surrounding soil disturbances.

However, predicted consolidation settlement in the field can be carried out without carrying out consolidation tests in the laboratory that can predict land subsidence based on field observations, by using the Asaoka [3] method. By applying this method, the actual amount of soil settlement can be predicted without requiring the soil parameters used in the consolidation analysis, such as pore water pressure, drainage length, maximum soil strain, and coefficients of consolidation. Also, in the Asaoka [3] method, the consolidation coefficient can be recalculated using the settlement data from the settlement plate instrumentation readings in the field. For this reason, this study emphasizes the calculation of a coefficient of consolidation value in soft clay soils that have been improved.

METHODOLOGY

Related Theory of Consolidation Time

The pre-compression method is an attempt to achieve a certain level of consolidation within a specified time limit. Based on a full-scale test of embankment consolidation installed using PVD, it shows that the soil subsidence due to consolidation that occurs is relatively smaller [4]. The average degree of consolidation, U, is measured by comparing the lost pore water pressure, U_d, with the initial pore water pressure, U_o, which is the pore water pressure when applied to a load or by comparing the settlement at a certain time, S_t, to the estimated primary settlement that will happen, S_f [5].

$$U = \frac{U_d}{U_o} = \frac{S_t}{S_f} \tag{1}$$

where U is the average degree of consolidation.

The time required to reach the average degree of consolidation due to pore water flow in the vertical direction, U_v, calculated according to the approximation Equation given by Terzaghi [5], is

for 0 % ≤ U_v ≤ 53 %

$$T_v = 0{,}25\,\pi\,(U_v/100)^2 \tag{2}$$

or

for 53 % ≤ U_v ≤ 100 %

$$T_v = 1{,}781 - 0{,}933\,\{\log(100 - U_v\,\%)\} \tag{3}$$

where T_v is a time factor.

Sivaram and Swamee [6] suggested an approximate calculation of the relationship between the average vertical consolidation degree and the consolidation time factor for the overall value, as shown in the following Equation (4).

$$U_v = \frac{\left(\frac{4T_v}{\pi}\right)^{0,5}}{\left[1+\left(\frac{4T_v}{\pi}\right)^{2,8}\right]^{1,79}} \tag{4}$$

The vertical consolidation time factor can also be obtained if the vertical coefficient of consolidation and thickness of the compressible soil layer are known.

In soft clay soils that have not been improved using PVD, the water flow occurs only in the vertical direction. The calculation of the consolidation time in the absence of PVD can be done using Equation (5). Meanwhile, in soft clays whose soil quality is improved using PVD, the flow of water will also occur in the radial direction. Calculation of the consolidation time of soft clay soil improved using PVD can be calculated using Equation (6) [7].

$$t = \frac{T_v H^2}{C_v} \tag{5}$$

$$t = \frac{T_r 4R^2}{C_h} \tag{6}$$

where C_v and C_h are the coefficients of consolidation in the vertical and horizontal directions in cm²/s, respectively. H is the thickness of the consolidated soil layer in cm and t in seconds which is the time required to reach the degree of consolidation U (%).

Literature Review

One of the critical conditions after infrastructure construction is a post-construction settlement. This greatly affects the service ability of the infrastructures. For this reason, consolidated settlements need to be predicted carefully. Based on the available settlement record for an embankment on soft ground, it can be concluded that the prediction of settlement using the hyperbolic method is significantly improved using the start of construction settlement data, notably, after more than 50% of the settlements have occurred [8].

Long-term settlement prediction using the early-stage data could be misleading. Therefore, observation in the field should also be performed. Settlement that will occur in the future at a site due to embankment loading could be predicted based on what is already happening at present. Large residual settlement may occur years after the construction is finished and enter into service. Tashiro et al. (2011) predicted settlement of naturally deposited clay ground due to embankment loading. The effect of modifying vertical section of the embankment by overlaying pre-compression layer to counter settlement was numerically analysed. Therefore, faster consolidation by applying a countermeasure could not be expected [9].

The long-term performance of the preloaded embankment was investigated. In order to predict the performance of the preloaded embankment, two fully coupled nonlinear finite element analyses were conducted by adopting an elasto-viscoplastic and an elastoplastic modified Cam Clay model to represent the soft clay. However, the prediction was not really in agreement with the observation values from the field [10]. Farnsworth (2013) predicted the settlement time rate of soft, compressible clayey soils improved by means of PVD. Prediction analysis performed by utilizing the finite difference technique [11].

Li (2014) proposed a simpler method to predict the embankment settlement in soft clays. The potential settlement and a simplified method were based on the in-situ data. The proposed method was verified by utilizing the theoretical method and field test data [12]. Many different methods in predicting the settlement of soft clay roadbeds were performed in detail. One dimensional consolidation theory of Terzahgi's theory [5] showed the correlation between consolidation degree, U, and time factor, T. The hyperbolic method [13] exhibited simple relation than the exponential curve.

Even though a simpler theory was developed to predict consolidation settlement, it is important and necessary to implement geotechnical observation in construction and loading to asses degree of consolidation and residual settlement of soft ground. Theoretically calculated data based on settlement observation was commonly bigger than that of technical design records [14]. However, Benamghar and Boudjellal (2017) found that consolidation settlement predicted using the hyperbolic model and field observation of embankment construction on soft clays are comparable and nearly identical with the final settlement [15]. The consolidation coefficient results from the Asaoka's method [3] are slightly larger than the hyperbola method results.

Furthermore, Shi (2018) found that Asaoka's method predicted the settlement trends once the consolidation degree exceeded 0.6 [16]. Subsequently, the prediction results of the settlement of soft clay can also be used to re-estimate the value of the consolidation coefficient. The assessment of the degree of consolidation prediction using the hyperbolic method is more conservative. It was recommended that determining the degree of consolidation from field settlement records was preferably [17]. Lakkoju et al. (2020) found that the hyperbola method was underestimating the consolidation coefficients by 1.26 times than that of the Asaoka's method. Although both Asaoka and hyperbola methods gave very good predictions of final settlement and consolidation coefficients, the accuracy of each method should be studied in further studies [18].

Materials and Instrumentation

The synthetic materials used for PVD in PLTU Riau was Colbond brand geotextile with type CX 1000, the width of 100 mm, and thickness of 3.80 mm, respectively. PVD diameter of 10 cm was installed with a distance from center to center of 150 cm.

The synthetic materials used for PVD in the proposed Makassar – Pare-pare railway lines were Alidrain brand of geotextile with type AD 230, the width of 100 mm, and thickness of 3.00 mm, respectively. PVD diameter of 10 cm was installed in triangular configuration with a distance from center to center of 100 cm.

The configuration of the PVD installation with a triangular and rectangular pattern is shown in **Figure 1**. Triangular and quadrilateral configurations underwent relatively the same time consolidation process. The consolidation settlement occurred by 3.80 meters with a time consolidation process of fewer than ten months. After ten months, the consolidation settlement did not occur again. This indicated that after ten months the degree of consolidation of 100% had been achieved. Without PVD, the consolidation settlement occurred at a maximum of 1.85 meters with a time consolidation process of more than 4 months [19].

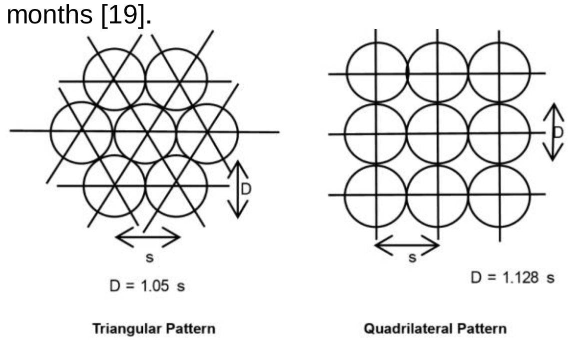


Figure 1. PVD Configuration pattern. [19]

In order to be able to monitor the magnitude of the settlement that occurs at the project site after the installation of PVD and the dissipated pore water pressure in the improved soil, it is necessary to install geotechnical instruments. The geotechnical instrumentation commonly used in pre-compression and vertical drain activities included settlement plates, piezometers, and inclinometers.

The settlement platform which is commonly called settlement plate, was used to measure land subsidence that has occurred on the ground surface. The piezometer is used to observe the dissipated pore water pressure. The inclinometer is used to detect the presence or absence of lateral deformation. **Figure 2** illustrates position of the instruments installed at the location of the study. Instruments installation at the site of study is shown in **Figure 3**.

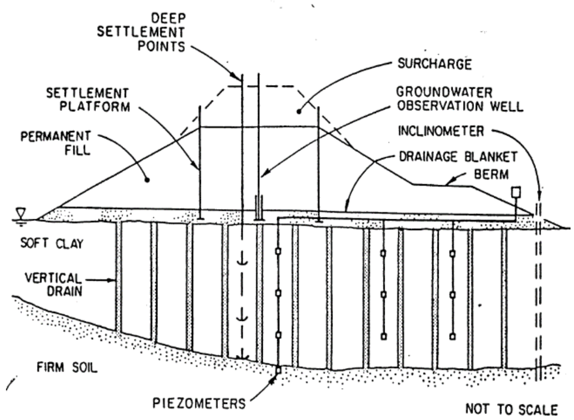


Figure 2. Typical instrument installation at PLTU Riau.

Figure 3. Installed instrumentations at site.

Interpretation of Monitoring Results

In general, data from the readings of the instrument were required for recalculation of the predicted value of the degree of consolidation. One of these data is settlement plate reading data. This settlement plate is an instrumentation that measures land subsidence due to pre-loading. The stages of the investigation to obtain the parameters needed in the study are shown in **Figure 4**. The interpretation of the observation results of instrumentation readings in the field has two main objectives: to evaluate the consolidation behaviour and assess the foundation's stability.

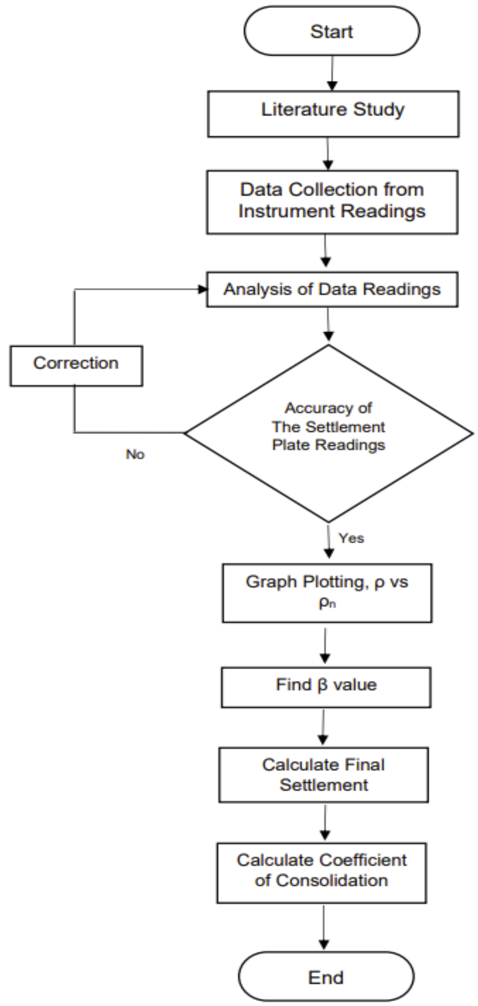
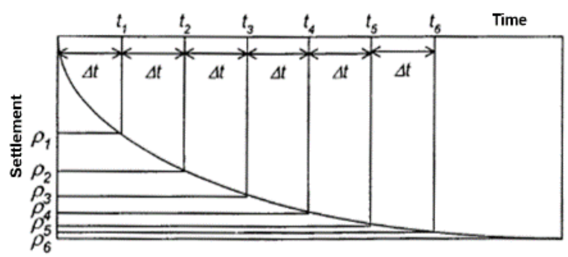


Figure 4. Study flow chart.

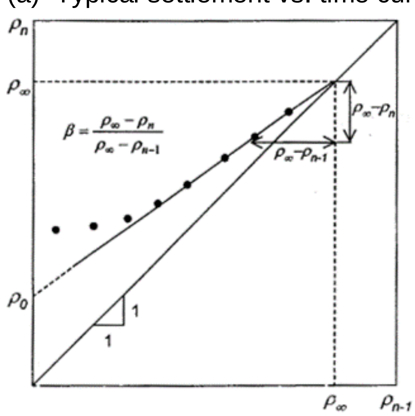
In order to achieve this goal, two analytical techniques are used; (1) the first is a direct estimation, for example, increasing the average rate of settlement and horizontal deformation indicating impending failure or pore water pressure measurements which provide data to estimate the vertical stress at a time required to stability analysis; and (2) secondly verification of design parameters, for example, the estimated horizontal coefficients of consolidation recalculated from piezometer and settlement data.

The method used to predict the coefficient of consolidation as a result of observations of the settlement in the field is Asaoka's method [3]. Asoaka's method is the most popular observation method and is often used because, in addition to predicting the final settlement, this method can also enable consolidation parameters to be obtained. In predicting the value of the consolidation coefficient by recalculation from observations of subsidence in the field, it is necessary to take steps as suggested by Asaoka [3]. From the plot of the time and settlement curves in **Figure 5**, select settlement points ρ_1, ρ_2, ... ρ_n, such that ρ_n is the settlement time at the time of t_n, and the time interval is the constant, $\Delta t = t_n - t_{n-1}$. The meeting points are the coordinates of (ρ_n, ρ_{n-1}). Furthermore, as shown in Figure 5 (b), these points form a straight line and are written in Equation (7).

$$\rho_n = \beta\,\rho_{n-1} + \rho_0 \qquad (7)$$



(a) Typical settlement vs. time curves



(b) ρ_n vs. ρ_{n-1} curves

Figure 5. Estimated final settlement according to Asoaka method. [3]

The final settlement, ρ_f, is expressed in Equation (8), while the settlement at time t, ρ_t, can be calculated using the following Equation (9).

$$\rho_f = \frac{\rho_0}{1-\beta} \qquad (8)$$

$$\rho_t = \rho_f\left\{1 - \exp\left(\left(\ln\frac{\beta}{\Delta t}\right)t\right)\right\} \qquad (9)$$

The constant β in Equation (9) is the slope gradient of the straight-line curve in **Figure 5(b)** and its value can be used to obtain the vertical and horizontal consolidation coefficients and are written as in Equation (10) and Equation (11).

$$C_v = -\frac{4H^2\ln\beta}{\pi^2\Delta t} \qquad (10)$$

$$C_h = \frac{(1-\beta)d_w^2F_n}{8\beta\Delta t} \qquad (11)$$

where,

- C_v = coefficient of consolidation in the vertical direction,
- C_h = coefficient of consolidation in the horizontal direction,
- H = the thickness of the consolidated soil layer,
- β = slope of the curve, ρ_n vs. ρ_{n-1},
- Δt = time interval during settlement observation, and
- F_n = vertical drain distance factor calculated using Equation (12).

$$F_n = \ln\left(\frac{D}{d_w}\right) - \frac{3}{4} \qquad (12)$$

- d_w = the diameter of one sand drain or the equivalent diameter (as in **Figure 6**) of one PVD, for the strip form is calculated by Equation (13)

$$d_w = \frac{2(a+b)}{\pi} \qquad (13)$$

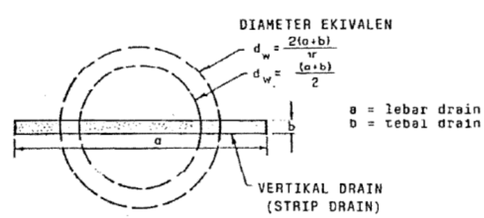


Figure 6. Synthetic drain vertical equivalent diameter. [19]

RESULTS AND DISCUSSION

Predicted Final Settlement

Field observations of the installation of this instrumentation were carried out in two different locations with relatively different geotechnical conditions. Study location 1 was at the proposed PLTU Riau, and study location 2 was at the proposed Makassar – Pare-pare railway line. In general, the geotechnical conditions were dominated by soft clays. At each study location where soil improvement carried out using PVD and pre-loading, were installed as many as ten settlement plate points to measure the settlement that occurred during soil improvement process. However, only 1 point of each location was used in this paper. In order to obtain the reasonable value of comparison between the calculation of the settlements in theoretical prediction and field observations, the locations of the settlement plates were arranged accordingly. The locations of the settlement plates point taken close to the result point soil tests used to calculate optimizing the use of the PVD.

Figure 7 represents the results of settlement readings. The two curves above zero level are showing the heights of the fill for loading compression. The two curves below zero level are indicating magnitude of settlement during pre-compression process. The horizontal axes is representing duration of pre-compression process in days.

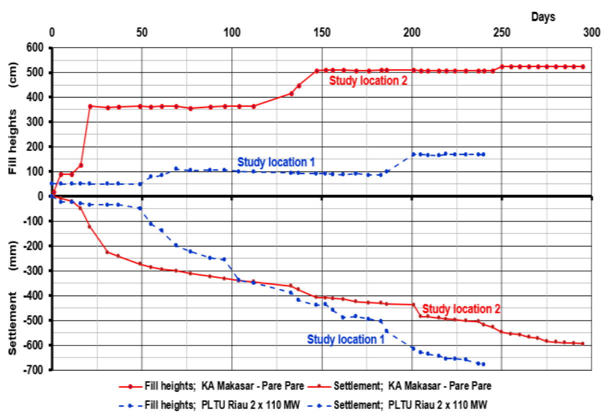


Figure 7. Settlement and fill heights plot of the settlement plate readings.

Figure 7 shows that the fill heights of study location 2 are higher than that of study location 1. The fill heights to get final compression at study location 1 and study location 2 were 168 cm and 519 cm, respectively. The compression process of study location 2 was achieved longer than that of study location 1. This indicates that the clay in study location 1 is softer than that of study location 2 to obtain similar pre-compression. The results of this observation were also shown in the settlement readings of the settlement plates. The settlement of study location 1 is bigger than that of study location 2. The settlement plate readings as in **Figure 7** shows that the maximum settlement of study location 2 was achieved with a longer time of consolidation process.

Figure 8 represents the maximum settlement obtained from the settlement plate readings at the two locations of the study after maximum soil fills were achieved to find maximum pre-compression. **Figure 8** shows that the maximum settlement at study location 1 is more significant than that at study location 2. The consolidation process at study location 1 is faster than that at study location 2. This condition indicated that the soil condition at study location 2 is harder and stiffer than that at location 1. It was realized that the configuration pattern of the PVD at both locations were similar. The pre-compression process at study location 2 took longer period of time. After the maximum heights of soil fills were achieved, the maximum settlement readings of the settlement plates were observed, and the final pre-compressions were analysed. At the final stage of the pre-compression, the final settlement at study location 1, and study location 2, were 678 mm, and 595 mm, respectively.

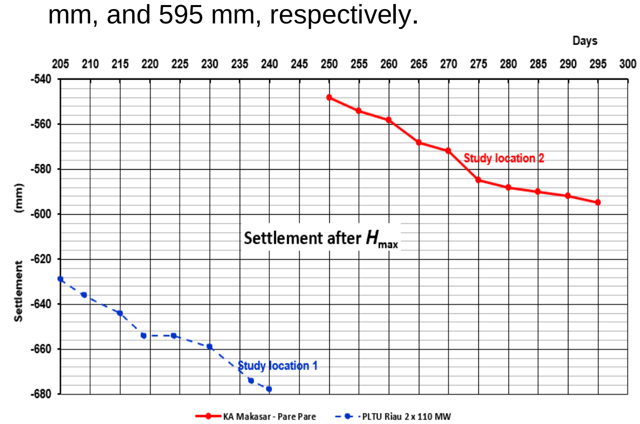
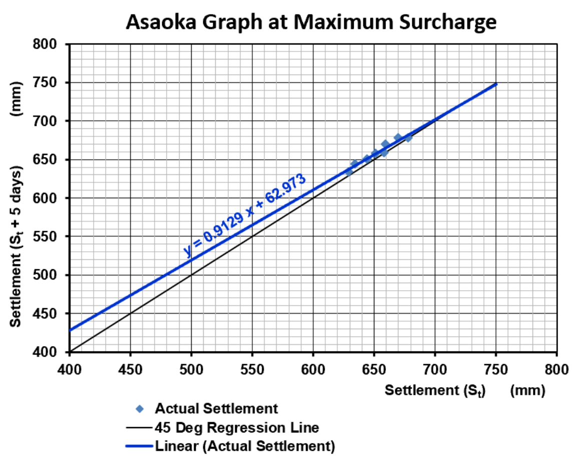


Figure 8. Settlement plot at the maximum height of soil fills.

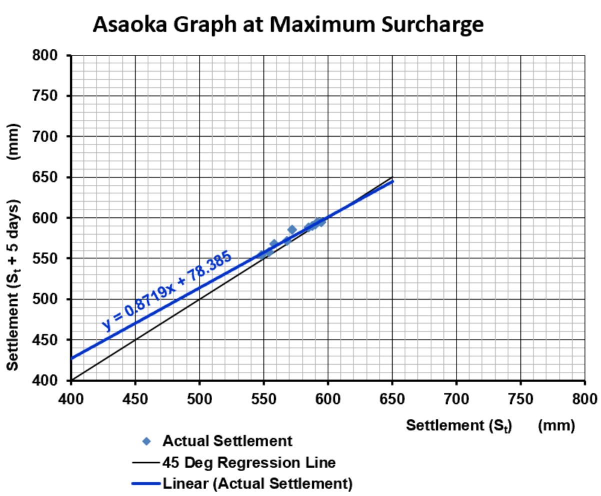
Back Calculation of Consolidation Coefficient

The final prediction of the soil settlement was obtained using Asaoka's method [3], which can be seen in **Figure 9**. **Figure 9(a)** represents settlement prediction of study location 1, and **Figure 9(b)** represents settlement plot prediction of study location 1. The settlement prediction at study location 1 began to be carried out on the day 205 of the settlement plate readings. The settlement prediction at study location 2 started to be done on the day 250 of the settlement plate readings. The settlement plate readings were then plotted onto **Figure 9**. It can be found from **Figure 9** that β_1 equals 0.9129, and β_2 equals 0.8719, respectively. The values of β_1, and

β_2 were calculated based on linear regression using statistical analysis program. The values of β_1 and β_2 indicated the linear regression gradient slopes. By corelating the value of ρ_n vs. ρ_{n-1}, the final settlement predictions were obtained. The final settlement prediction of study location 1, the settlement prediction of study location 2 were 723 mm, and 595 mm, respectively. The degree of consolidation achieved at study location 1, and study location 2 were 94% and 97%, respectively. The settlement prediction obtained from Asaoka's method [3] is greater than that of field observation using the settlement plate readings. This finding is in agreement with the results reported by Le et al. [14] and Shi [16].



(a) Study location 1 (the proposed PLTU Riau)



(b) Study location 2 (the proposed KA Makasar-Pare-pare)

Figure 9. Prediction of the final settlement using Asaoka's method.

Asaoka's method is better to be used in predicting the magnitude of total settlement that occurs in the field. The results obtained are closer to the settlement data which exists. In actual conditions in the field, many unexpected phenomena and external factors can affect the magnitude of the total settlement. This is because the Asaoka method is overrated to represent the actual conditions in the field. In addition, Asaoka's method predicts final settlement based on available field data [20].

Figure 9 shows values of β, therefore by applying the afford mention β into Equation (10) and Equation (11), the coefficients of consolidation can be found. By considering interval time of settlement plates of readings at every additional five days, the predicted vertical consolidation coefficients (C_v) and the predicted horizontal consolidation coefficients (C_h) at study location 1 were 0.1626 cm^2/sec and 1.979 x 10^{-6} cm^2/sec, respectively. At study location 2, the predicted vertical consolidation coefficients (C_v) and the predicted horizontal consolidation coefficients (C_h) were 0.2344 cm^2/sec and 2.550 x 10^{-6} cm^2/sec, respectively. These values are not far from the values reported by Aspar et al. (2017) [21].

CONCLUDING REMARKS

From the results of prediction analysis, the facts are obtained and are presented as follows. This paper has described prediction analysis on the coefficient of consolidation values in improved soft clays. By considering interval time of settlement plates readings, the coefficient of consolidation can be predicted accordingly.

The geotechnical instrumentations installed in pre-compression and vertical drain activities during the field observation were beneficial in providing appropriate geotechnical data. Data from the readings of the instrument were utilized for back-calculation of the predicted value of the degree of consolidation, settlement, and the coefficient of consolidation.

Field observations and analytical prediction results showed that the settlement prediction obtained from Asaoka's method was greater than the settlement reported from the field observation using the settlement plate readings. Nevertheless, prediction by Asaoka's method is better to be used provided field observation readings giving accurate data. This is because the Asaoka method represented the actual conditions in the field.

AUTHOR INFORMATION

Corresponding Authors
Email: eka_nf@mercubuana.ac.id
Phone: +62 813-2216-4210

Author Contributions
All authors performed their duties based on their competence for this work, and contributed equally to this paper.

ACKNOWLEDGMENTS

Monitoring instrumentation at the PLTU Riau was performed by PT. Geohub Entraco Prima, Tangerang, Banten. Pre-fabricated vertical drain (PVD) was utilized for soil improvement at the Project locations. The PVDs were installed by PT. Pandu Equator Prima, Bekasi, Indonesia. The authors declare that there is no conflict of interest regarding the publication of this paper.

REFERENCES

[1] Shen, S.-L., Chai, J.-C., Hong, Z.-S., and Cai, F.-X., "Analysis of field performance of embankments on soft clay deposit with and without pvd-improvement," *Geotextiles and Geomembranes*, No. 23, pp. 463-485, Elsevier Ltd., Philadelphia, USA, 2005.

[2] Basu, P., Basu, D., and Prezzi, M., "Equal-strain analysis of PVD-enhanced consolidation considering soil disturbance," *Proceedings of the 12th. International Conference of International Association for Computer Methods and Advances in Geomechanics*, pp. 3612-3620, Goa, India, 1-6 October 2008.

[3] Asaoka, Akira, "Observational procedure of settlement prediction, "*Soils and Foundations*, Japanese Society of Soil Mechanics and Foundation Engineering, Vol. 18, No. 4, Dec, 1978.

[4] Pothiraksanon, C., Bergado, D. T., and Abuel-Naga, H. M., "Full-scale embankment consolidation test using pre-fabricated vertical thermal drains," *Soils and Foundations*, Japanese Geotechnical Society, Vol. 50, No. 5, pp. 599-608, October, 2010.

[5] Das, B. M., *Principles of Foundation Engineering*, 8th, Cengage Learning, Stanford, USA, 2016.

[6] Sivaram, B., and Swamee, P., "A Computational method for consolidation coefficient," *Soils and Foundations*, Vol. 17, No. 2, pp. 48-52, Tokyo, Japan, 1977.

[7] Ong, C. Y., Chai, J. C., and Hino, T., "Degree of consolidation of clayey deposit with partially penetrating vertical drains," *Geotextiles and Geomembranes*, No. 34, pp. 19-27, Elsevier Ltd., Philadelphia, USA, 2012.

[8] Huat, B. B. K., Hoe, C. Ng, and Munzir, H. A., "Observational methods for predicting embankment settlement," *Pertanika Journal of Science and Technology*, Vol. 12, No. 1, pp. 115-128, 2004.

[9] Tashiro, M., Noda, T., Inagaki, M., Nakano, M., and Asaoka, A., "Prediction of settlement in natural deposited clay ground with risk of large residual settlement due to embankment loading," *Soils and Foundations*, Japanese Geotechnical Society, Vol. 51, No. 1, pp. 133-149, Feb., 2011.

[10] Islam, M. N., Sivakumar, S. T., and Karim, M. R., "Long-term performance of preloaded road embankment," *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering - Challenges and Innovations in Geotechnics,* Vol. 1, pp. 1291-1294, Paris, 2013.

[11] Farnsworth, C. B., Barlett, S. F., and Lawton, E. C., "Estimation of time rate of settlement for multi-layered clays undergoing radial drainage," *Transportation Research Record: Journal of the Transportation Research Board*, No. 2363, Transportation Research Board of the National Academies, pp. 3–11, Washington, D.C., 2013.

[12] Li, Chunlin, "A simplified method for prediction of embankment settlement in clays," *Journal of Rock Mechanics and Geotechnical Engineering*, Vol. 6, No. 1, pp. 61-66, 2014.

[13] Tan, S. A., "Hyperbolic method for settlements in clays with vertical drains," *Canadian Geotechnical Journal*; Vol. 1, No. 31, pp. 125–131, 1994.

[14] Le, H. V., Pham, B. T., Ho, L. S., Nguyen, M. D., "Analysis of consolidation degree using settlement observation results and Asaoka method: A case study of route km 94+340 -:- km 94 + 440 of Hanoi - Haiphong highway construction project," *International Journal of Civil Engineering and Technology* (*IJCIET*), Vol. 8, Issue 11, November 2017, pp. 91-100.

[15] Benamghar, A., and Boudjellal, M., "Comparative study of four consolidation settlement estimation methods of a railway embankment," *MATEC Web of*

Conferences, Vol. 120, (ASCMCES 17), April 18-20, 2017.

[16] Shi, B., and Kong, X., "Study on methods for predicting the settlement of soft clay roadbed*," Proceedings of the 1st International Congress and Exhibition - Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology*, GeoMEast 2017, Frikha et al. (eds), Egypt, Springer International Publishing AG 2018 W., pp. 370-377.

[17] Kumar, V., and Islam, A., "Evaluating degree of consolidation of soft soil by using Asaoka, hyperbolic and back analysis method," *Proceedings of DFI-India 2017: 7th Conference on deep foundation technologies for infrastructure development in India*, January, 2019.

[18] Lakkoju, V., Kommu, S., Reddy, M. M., Sony, B., and Asadi, S. S., "In-situ consolidation analysis by Asaoka and hyperbola methods," *International Journal of Scientific & Technology Research*, Vol. 9, Issue 02, pp. 6296-6302, February 2020.

[19] Aspar, W. A. N., and Fitriani, E. N., "Effect of distance and pattern of pre-fabricated vertical drain for improvement of soft clay soil," *Majalah Ilmiah Pengkajian Industri*, Vol. 10, No. 1, April 2016, pp. 41-50.

[20] Nawir, H., Apoji, D., Fatimatuzahro, R., and Pamudji, M. D., "Prediksi penurunan tanah menggunakan prosedur observasi Asaoka studi kasus: Timbunan di Bontang, Kalimantan Timur," *Jurnal Teoretis dan Terapan Bidang Rekayasa Sipil*, Vol. 19, No. 2, pp. 133-148, August 2012.

[21] Aspar, W. A. N., Fitriani, E. N., and Arthono, A., "Perhitungan kembali nilai koefisien konsolidasi pada perbaikan tanah lempung lunak," *Jurnal Teknologi*, Vol. 7, No. 1, January 2017.