International Journal of GEOMATE, Aug., 2021, Vol.21, Issue 84, pp.93-102
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2021.84.j2151
Geotechnique, Construction Materials and Environment

THE COMPARISON OF THE SOFT CLAY SETTLEMENT UNDER AN EMBANKMENT LOAD USING FIELD INSTRUMENTATION AND EMPIRICAL FORMULATION

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*Corresponding Author, Received: 28 March 2021, Revised: 04 May 2021, Accepted: 12 June 2021

ABSTRACT: Settlement of embankments on soft soils is a significant problem in geotechnical engineering to maintain pavements, buildings, and other facilities on them. The problem that often arises is not being able to predict the magnitude of consolidation compression accurately, this occurs due to uncertainty in field conditions, laboratory testing, and data interpretation, as well as assumptions made in the development of 1-D consolidation theory. Based on the causes of inaccurate settlements predictions, it is necessary to carry out research on a better method for predicting embankment's settlement on soft soil. To obtain the correct method, a study was conducted by comparing and examining the consolidation settlement of embankments built on soft soil using theoretical calculations and field measurement results. The process involved monitoring the settlements using 25 plate measurement data in embankment preloading for housing and building construction over the very soft clay. The results showed the compression parameter, especially Cc, is very influential on the compression ratio, and the Cc value based on the empirical formula of Bowles (1989) turned out to be the most suitable for the actual compression results in the field with a compression ratio between 0.6-1.1 and confidence of level 90%.

Keywords: Soil settlement, 1-D consolidation, Compression index, Settlement field monitoring, Settlement comparison.

1. INTRODUCTION

1.1 Background

The design and construction of embankments on soft soil is one of the important critical challenges associated with problems in the geotechnical field, namely settlement and stability of embankments. The magnitude of settlement is significant for the serviceability of structures and equipment in constructing infrastructures such as road and reclamation embankment. Meanwhile, excessive settlement under embankment structures has the can cause cracking, fractures, and potential structure and, or equipment failures.

Soft soil or clay foundation usually has a low bearing capacity and high compressibility. This means the deposits need to be treated before the construction of any structure to reduce problems. Several improvement techniques have developed, but pre-consolidation using prefabricated vertical drain (PVD) and preloading or surcharge fill is one of the most popular and effective techniques in practices. According to Indraratna [1] and Nazir, Moayedi, Subramaniam and Gue [2], this method has a relatively low cost, easy to install, and the PVD can reduce compression time by almost ten times by accelerating radial consolidation through the reduction of drainage pathways. Moreover, the installation process is relatively fast and has little impact on the environment. Long, Bergado and Balasubramaniam [3] reported using this technique with and without the vacuum method is the most frequent choice for soil improvement in Southeast Asia. Furthermore, consolidation compression is the event of compressing the soil due to additional loads that involve removing pore water from the soil by means of squeezing, and this process can be accelerated through the installation of PVD to provide a channel for water flow and shorten the water flow path in soil which has a low permeability coefficient. In accordance with the PVD function, where PVD can only accelerate the completion time of settlement consolidation but cannot reduce the magnitude of settlement. Therefore, it is necessary to evaluate what parameters affect the magnitude of settlement that occurs.

The evaluation of expected settlements depends on the determination of consolidation parameters through a laboratory test, field test, and empirical correlation. Researchers have examined possible causes of parameter inaccuracies obtained from laboratory tests due to several factors including sample disturbance, sample size, and strain rate. For the field test, the total settlement that occurred based on the observation of settlement plate in several locations was the actual settlement in the field. The actual results in the field for various

locations were compared with settlements calculated based on laboratory and field tests.

1.2 Related Work

Several attempts have made to compare the consolidation settlement data from laboratory tests using the empirical formula and actual data from the field. For example, Oakley and Richard [4] found the time rate was within 150% of the actual field measurement, while Crawford and Companella [5] reported the actual to be approximately 60% was higher than the calculated average data. Moreover, Liu, Cai and Puppala[6] studied eight sites and found the data from laboratory test to be 13-72% were lower than field measurement while Abu Farsakh Pant, Gautreau, and Chen [7] and Abu Farsakh Yu, and Gautreau [8] compared the calculated settlements using CPT and laboratory test with the instrumented embankment of measured settlements and found an overprediction with the use of the CPT and laboratory tests.

Salem and El-Sherbiny [9] also showed the use of one-dimensional consolidation theory through the application of the laboratory test and CPT for under-consolidated clays reasonably estimated the magnitude and rate of consolidation settlement and also proposed the measurement of compression on different field locations to evaluate the inaccuracy and compare the settlement calculations from both laboratory and field tests. Furthermore, a previous study by Vipulananda [10] reported on 40 consolidation tests and settlement monitoring measurements in two highway embankments for 20 months and found the predicted data to be comparable with those measured in the field. Nazir Sukor, Niroumand, and Kassim [11] also studied the performance of soil instrumentation using five settlement plate measurements to predict soil settlement The prediction results of the total data showed that the classic one-dimensional consolidation were proportional to the actual data recorded on the site.

Another study was conducted by Khouri and Haque [12] to compare actual soil compression using geotechnical instruments and empirical calculations. Khouri and Haque [12] used several methods such as pressure meter tests (PMT), dilatometer tests (DMT), Standard Penetration Tests (SPT), cone penetration tests (CPT), and a settlement plate. The research compared the bearing capacity and settlement predictions based on the different in-situ tests used for the building in northern Virginia, and the SPT and CPT observation were overestimated. At the same time DMT and PMT predicted lesser than data observed in the field using the settlement plate. These results showed the settlements predicted by DMT and PMT can represent the actual values. Another researcher, Leclair [13] also found the predicted value of compression using the compression formula from the CPT data, the prediction result showed approximately 10% greater than the actual data from the field.

Moreover, another study on the compression index was conducted by [14] who obtained a new empirical formula, namely Cc = 0.506eo-0.11. This study has examined more than 130 undisturbed specimens obtained from different depths which are results of two years geotechnical studies located at south-west of Iran. Habibbeygi and Nikraz [15] obtained a new CC formula for remolded clay, namely $Cc = 0{,}666e_L - 0{,}830e_p$; Daoud, Kasama, Saleh, Negm [16] declared the best correlation for Cc is 0,2608e and Cc = 0,0093Wc, and Sari and Firmansyah [17] also obtained a new Cc formula, namely Cc = 0.6787eo- 0.1933 obtained from 466 soil samples from 77 points of data bore holes at 25 locations spread in Surabaya area. Those empirical formulations were not used in this study because the data used is only valid for the local area. Several other studies conducted to compare and analyze the actual compression on the field and empirical calculations for embankment planning and compression index correlation include [18-21].

These studies indicate variations in the comparison of the actual and predicted settlement magnitude and this is due to several factors, one of which is the inaccuracy of the consolidation parameters used in predicting the settlement. For example, a small amount of sample data is usually used in laboratory tests to obtain consolidation parameters based on economic reasons and time considerations, and this means the calculation is often carried out using empirical formulas and correlations [22], which are required to be selected appropriately following the soil conditions of the locations to reviewe. It means the factors affecting the variations include the different conditions and types of soil and the empirical formulations to obtain the parameters of the placement.

The difference in the empirical formula to obtain the value of the compression parameter, Cc, is the main focus of this study. Comparing of the actual compression in the field and the predicted value of compression using different empirical formulations to obtain the Cc value can be used to determine the formula with the closest value to the field conditions based on the settlement plate test. The embankment used in this study is currently under construction in a residential and building construction area in the West Java region. In that area, ground improvement was conducted before the construction as started using PVD and surcharge preloading with field observation instrumentation of more than 20 settlement plates installed in different areas to monitor soil settlement. Furthermore, the challenging subsurface conditions,

field monitoring data, and comparison between the measured soil settlement from the settlement plate result and empirical formula using conventional calculation methods are presented in this study.

2. GEOTECHNICAL DATA

2.1 Soil Parameter

The construction of any structure in the compressible layer of soil usually requires finding the solution to the soil settlement problem. It is influenced by the compression index, Cc, or the volume change coefficient, mv. The knowledge of the rate at which subsoil settlement occurs is essential for design considerations, and this compression parameter is considered necessary in preloading techniques for soil improvement [23]. It is also important to note that soil settlement parameters and characteristics are significant in geotechnical engineering to predict the soil settlement, especially when the soil subgrade is cohesive.

This research was conducted by PT.–Testana Indoteknika (incorporated company) using 11 soil data at the preloading for building and housing areas in Bandung, West Java with each point having 3-5 soil samples at different depths which were used for laboratory test. The results of laboratory tests include obtaining physical soil parameter using volumetric and gravimetric soil, consolidation parameter using oedometer test at few depths, and soil shear strength parameters using direct shear and unconfined test. Most of the soil in the study location was observed to be soft clay, and the recapitulation of the parameters used is indicated in Figure 1.

The main parameter used to calculate the settlement is the value of the compression index (Cc) but not all the soil depths were tested for consolidation. Therefore, this study uses the application of an empirical formula to calculate the compression after which comparative analysis is carried out.. This study also applied 15 empirical formulations indicated in the Table to calculate the compression index value, which is further used to evaluate the settlement data The values of the Cc produced from the empirical formula varies widely, and this is due to the differences in the soil parameters used in the calculation as shown in Figure 2. Figure 2 presents the values obtained from the empirical formula at each depth with laboratory data only at the BH-1 and BH-2 locations as an anlysis result that represent the other points.

The calculation of the Cc value presented in Figure 3 shows the difference in the values tends to be significant in one formula in comparison to another. Furthermore, the consolidation test analysis in the laboratory also produced parameter values that tend to be different from those obtained by the empirical formula. Recapitulation of soil data used in this study can be seen in Table 2

Table 1 The empirical formulation of the compression index calculation used in this study

Equation	Reference
0.007. (LL-7)	Skempton (1944)
0.009.(LL-10)	*Terzhagi and* Peck (1967)
(LL-13)/109	Mayne (1980)
0.009. (LL-13)	Biarez (1994)
0.0055. (LL-1.8364)	Vinod and Bindu (2010)
0.5.Gs.IP/100	Wroth and Wood (1978)
1.15. (eo-0.35)	Nishida (1956)
0.54.(eo-0.35)	Nishida all clay (1956)
0.35.(eo-0.5)	Hough (1957)
0.43.(eo-0.25)	Cozzolino (1967)
(0.156.eo)+0.0107	Bowles (1989)
0.0115.Wc	Moran (1958)
0.01.(Wc-5)	Azzouz (1976)
0.01.Wc	Koppula (1981)
0.01.(Wc-7.549)	Herrero (1983)

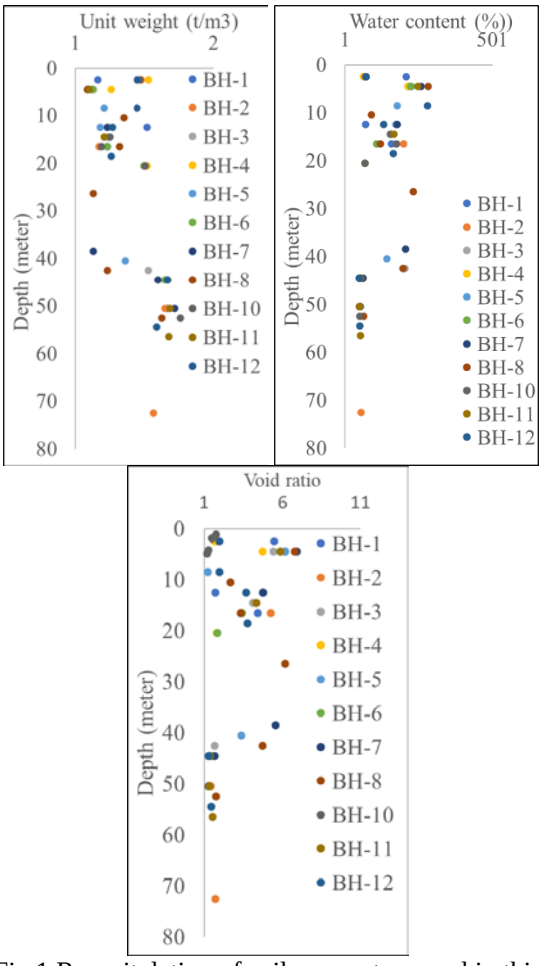

Fig.1 Recapitulation of soil parameters used in this study by PT.—Testana Indoteknika (incorporated company)

Tabel 2. The recapitulation of soil data

Bore Hole	Depth (m)	Cc
BH-1	12.5	1.1
	16.5	3.3
	50.5	0.852
BH-2	50.5	0.733
	72.5	0.836
BH-4	4.5	1.98
	20.5	0.925
BH-5	8.5	1.473
BH-6	16.5	1.635
	20.5	0.905
BH-7	12.5	1.291
	38.5	2.409
	44.5	0.14
	50.5	0.679
BH-8	26.5	2.036
	42.5	2.079
	52.5	0.71
BH-10	14.5	2.497
	20.5	0.731
BH-11	44.5	0.571
	56.5	0.765
BH-12	18.5	1.436

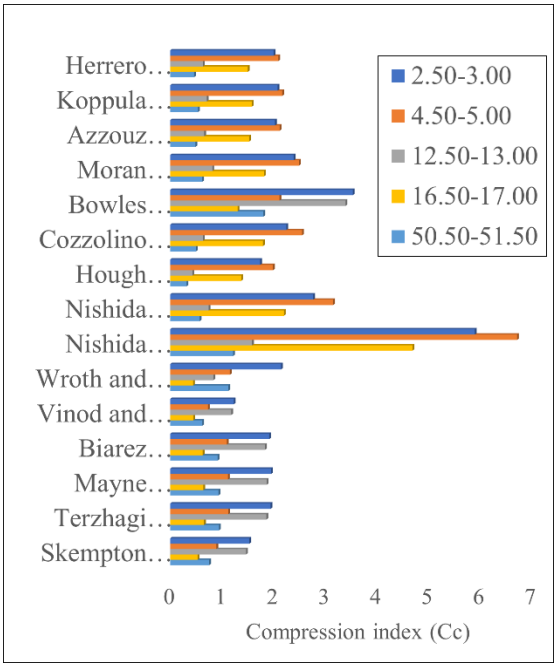

Fig.2 Comparison of the compression index (Cc) values in the 15 empirical formulas used at the BH-1 location

It was discovered that not all soil parameters present at all depths were used to calculate the settlement, only parameters in the compressible soil later used to calculate. The Soil parameters were obtained based on the correlation of the N-SPT test value with soil consistency and found to be between 20-30 meters.

2.2 Settlement Plate

This research used 25 settlement plate data scattered all over the construction area, and the predictions calculated based on 1-dimensional compression ~~were~~ has compared with the ~~real~~ actual values from the field by grouping the study area into ~~3~~ three, which ~~are~~ is Area A consisting of settlement plates SP-1, SP-2, SP-7, SP-8, SP-13, SP-14, SP-15, SP 19 and SP-20 with soil data BH-1, BH-2, BH-3, BH-4, BH-5 and BH-10, Area B consisting of SP-3, SP-4, SP-9, SP-10, SP-16, SP-17, SP-21 and SP-22 with BH-6, BH-7, BH-8 and BH-10, and Area C consisting of SP-12, SP-25 and SP-24 with BH-12.

The embankment preloading was carried out in the field at different heights, 5 to 6 meters. Produce different compressions at each location, and the settlement was observed on the soil subgrade under the embankment load at each point based on the settlement plate observations shown in Figure 5. Moreover, the embankment was loaded at the top elevation to reach the final settlement based on the Asaoka formula predictions, which showed the settlement times between 350 to 400 days. The summary of the settlement plate result and embankment height at each study area is~~,~~ shown in Figure 3.

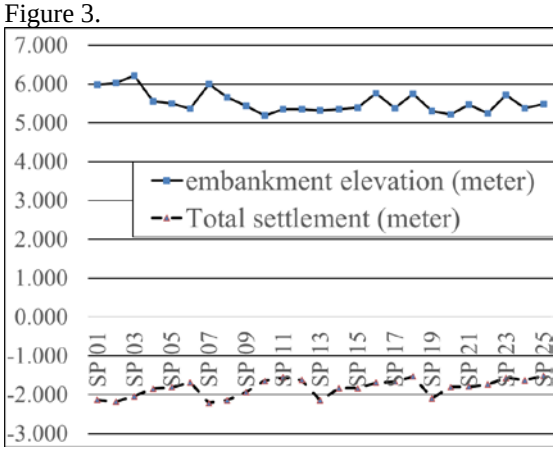

Fig 3 Summary of the settlement plate observations (total settlement) at each instrument placement point

3. SETTLEMENT CALCULATION METODOLOGY

During construction, loads from structures are transmitted to the underlying sub-surface soil. As a result, stresses increase within the structure and the soil mass undergoes vertical settlement. The total settlement, S, is calculated as the sum of the three components that is immediate settlement,

consolidation settlement and the secondary compression settlement. Cook [24] in his study stated that settlement is about the changes of soil volume following a reduction of the void space, which is caused by a change of confining pressure. The change of confining pressure in this case is due to the embankment load on it.

Another study by Fox [25] stated that, the consolidation settlement occurs as the result of volumetric compression within the soil. For non-cohesive soil, the consolidation process is sufficiently rapid so that the consolidation settlement is generally included with immediate settlement. Cohesive soils have a much lower hydraulic conductivity, as a result, consolidation requires a longer time to complete. In this case, consolidation settlement is calculated separately from immediate settlement. This research only focuses on settlement consolidation analysis for cohesive soil.

Based on Fox [25], when a load is applied to the soil surface, there is a tendency for volumetric compression of the underlying soils. Increasing pore water pressure in saturated soils occurs immediately upon load application. Gradually there is a process of reducing the volume due to the discharge of water from the soil pores. This process is called consolidation. Furthermore, the excess pore water pressure dissipation is accompanied by an increase in volumetric strain and effective stress. Analysis of the resulting settlement is greatly simplified if it is one-dimensional for strain, occurring only in the vertical direction [25].

Based on Leonard [26] , the assumption of one-dimensional compression is considered to be reasonable when the width of the loaded area exceeds four times the thickness of the clay stratum; the depth to the top of the clay stratum exceeds twice the width of the loaded area, or the compressible material lies between two stiffer soil strata whose presence tends to reduce the magnitude of horizontal strains. This assumption is accordance with the area conditions used in this study, so that this study uses one-dimensional compression in its analysis

The planners in the study area did an embankment preloading as high as 5-6 meters with PVD to resolve the settlement before the building was constructed, which led to the rapid occurrence of the settlement than without PVD. The settlement was calculated using the primary consolidation formula on clay using two assumptions which are over-consolidated (OC) and normally consolidated (NC) soils. This formula was made due to the review of incomplete test data consolidation at each depth, especially on the pre-consolidation stress parameter applied to calculate the over-consolidated ratio and further determine the status of the soil as either OC or NC. Meanwhile, the pre-consolidation stress parameter was only found at deep elevations with OC soil conditions and the consistency at this depth is a hard soil layer based on the correlation with the N-SPT data to ensure it is not a compressible soil layer. Therefore, the NC and OC assumptions were compared with the compression recorded in the field. The consolidation on the soil compression for OC, and NC was formulated using the following relationships.

$$\mathbf{Sc_{(NC)}} = \frac{\mathbf{H}}{\mathbf{1+e_o}}\left[\mathbf{C_c log}\left(\frac{\mathbf{\sigma' o+\Delta\sigma}}{\mathbf{\sigma' o}}\right)\right] \quad (1)$$

$$\mathbf{Sc_{(OC)}} = \frac{\mathbf{H}}{\mathbf{1+e_o}}\left[\mathbf{C_s log}\left(\frac{\mathbf{\sigma' o+\Delta\sigma}}{\mathbf{\sigma' o}}\right)\right]$$

if $(\sigma_o' + \Delta\sigma) \leq \sigma_c'$ (2)

$$\mathbf{Sc_{(OC)}} = \left[\frac{\mathbf{H}}{\mathbf{1+e_o}}.\mathbf{C_s log}\left(\frac{\mathbf{\sigma' c}}{\mathbf{\sigma' o}}\right)\right] + \left[\frac{\mathbf{H}}{\mathbf{1+e_o}}.\mathbf{C_c log}\left(\frac{\mathbf{\sigma' o+\Delta\sigma}}{\mathbf{\sigma' c}}\right)\right]$$

if $(\sigma_o' + \Delta\sigma) > \sigma_c'$ (3)

Where eo is the void ratio, σ'o is overburden stress, σ'c is pre-consolidation stress, Δσ is stress distribution, Cc is index compression, Cs is the swelling index, and H is the soil layer thickness.

The variation in the values of Cc and Cs based on the 15 empirical formulas was used to calculate the compression using the following formula as well as through

4. SETTLEMENT ANALYSIS

4.1 Settlement calculation based on empirical formula

The settlement was calculated at 11 locations with the thickness in each layer associated with the data from the boring test in the field and the N-SPT test. The soil layers at each location were, and the compression was calculated only at an incompressible soil depth with an N-SPT value of less than 10. The results are summarized into several comparison charts for each cluster area under review and displayed based on two assumptions which are NC and OC soil, as shown in Figure 4 to 6.

The results of the settlement calculation with the variations used in this study showed the existence of striking differences between one formula and another. Moreover, the difference in yield was not limited to the soil assuming NC but also found with OC. It was discovered that Bowles (1989) had the smallest compression value while Nishida (1956) had the highest and the values were observed to be

irrational but Biarez (1994), Herrero (1983), Koppula (1981), and Moran (1958) produced relatively large values for the two soil assumptions. Therefore, the compression generated using Cc from the lab data was too large and tends to make no sense.

4.2 Field Monitoring

The field was monitored at 25 points for 350-400 days and conducted routinely with a maximum observation range of 1 week. The process involved the installation and observation of settlement plate monitoring soil after the embankment height of 1-1.5 meters, while the compression was recorded immediately after the first stage of the embankment fill process at several locations, including SP12, SP24, and SP25, to ensure the settlement magnitude at the beginning is minimal.

Moreover, the embankment stage construction lasted approximately four months up to the moment it reached the top elevation of 5.5-6 meters which varies with the location. The recapitulation of settlement plate observation results in all distribution areas is presented in Figure 7 with more sloping compression graph observed after the 120th day. The slope shows the compression in the field on the day of observation was close to the total compression, and this was further proven by calculating the total compression on the representatives of 5 settlement plates using the Asaoka method and over 90% was observed to have been found on the field.

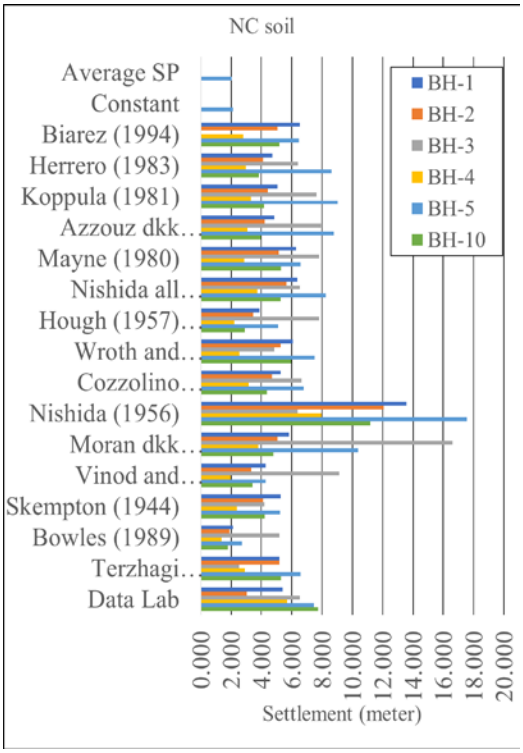

Fig 4a Settlement calculation results (Area A-NC soil)

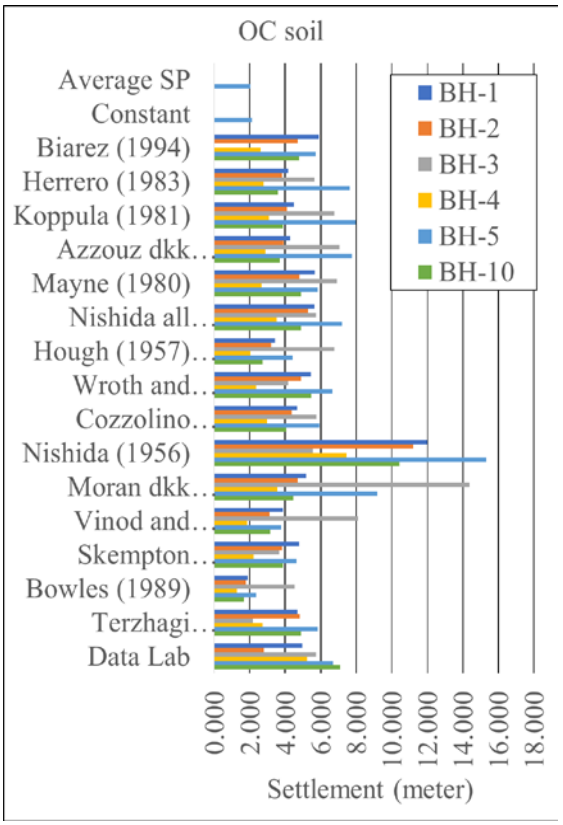

Fig 4b Settlement calculation results (Area A-OC soil)

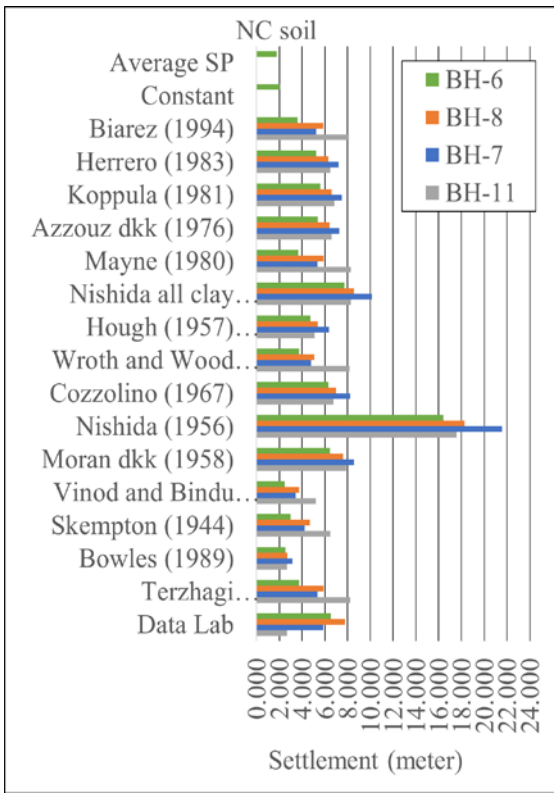

Fig 5a Settlement calculation results (Area B-NC soil)

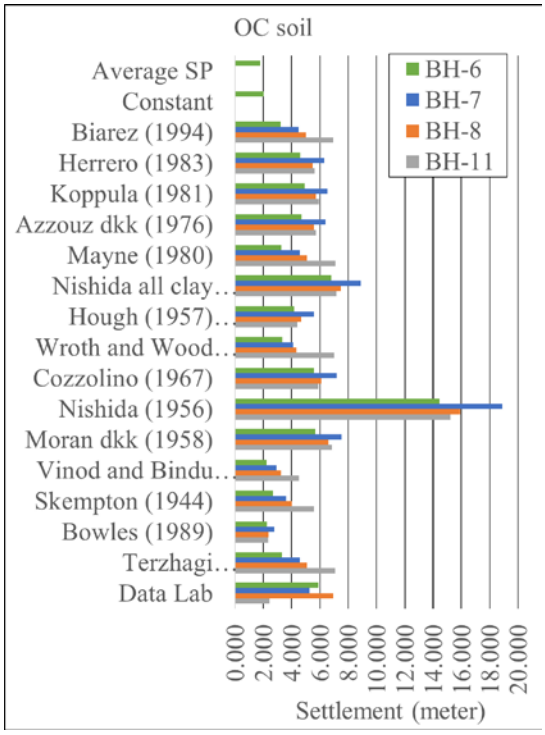

Fig 5b. Settlement calculation results (Area B-OC soil)

5. RESULT AND DISCUSSION

The settlements calculated during one year of loading were compared to those measured at the twenty-five settlement plates location. The predicted compression with Cc value varied produced results which tend to be higher than the results of the field monitoring with the Bowles' (1989) formula found to be the most appropriate. Moreover, the compression calculated using the constant index method also produced results that are almost the same as the field monitoring settlement under specific constant index values. However, ~~but~~ the determination of constant index value is also a problem due to the too extensive range of correlation values for a particular soil type.

Nishida's (1956) formula had the highest results followed by Moran (1958), Cozzolino (1967), and others and this was found to be different from the research of [27] which showed more conservative or larger values of Cc were predicted by Cc = 0.009 (LL-10) (Terzaghi and Peck 1967) while those provided by Cc = 0.0046 (LL-9) (Cozzolino, 1961) were much smaller. Meanwhile, the two formulas in this study used liquid limit parameters even though the LL parameter was minimal. This was probably associated with the difference in the results when compared to previous studies. Al-Khofaji et al. [28] also stated that Cc = 0.054(eo - 0.35) (Nishida 1956) and Cc = 0.35(eo - 0.50) (Hough 1957) appear to give an upper and lower bound, respectively, for the compression index for void ratios greater than 0.50 and the Nishida (1956) formula [Cc = 0.54(eo - 0.35)] was the best fit over the entire range of void ratios. This means Nishida (1956) Cc=0.54(eo - 0.35) was recommended by previous studies over Cc = 1.15(eo - 0.35) and this produced unreasonably conservative values for the compression index

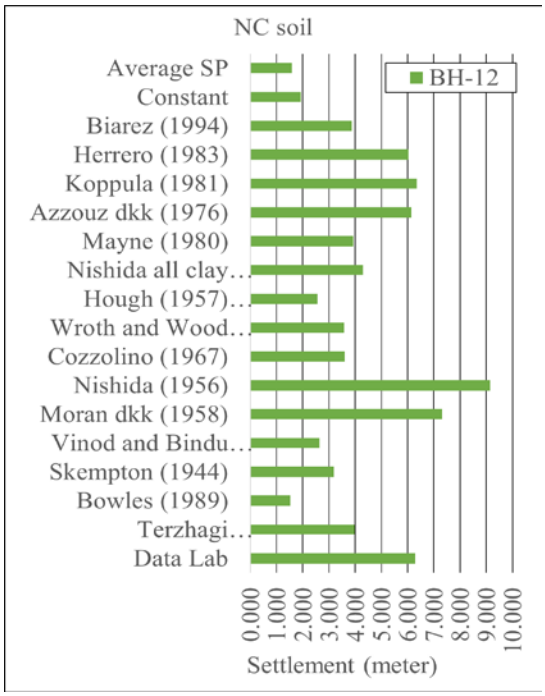

Fig 6b Settlement calculation results (Area C-NC soil)

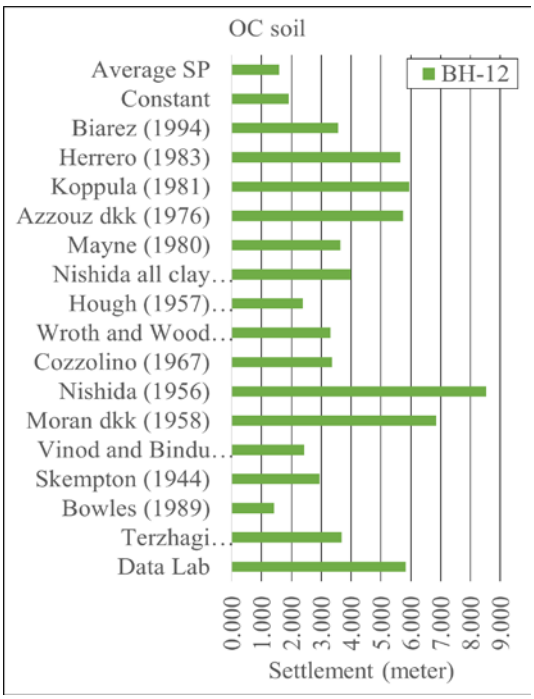

Fig 6 Settlement calculation results (Area C)

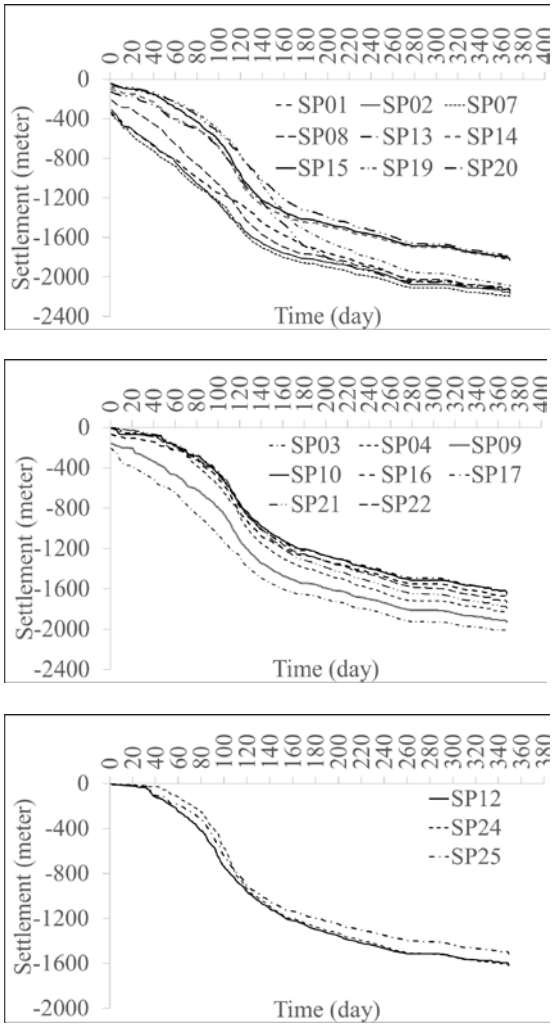

Fig 7 Settlement plate observations in each division of the study area

The same results were obtained in this study. The compression calculated using the laboratory data was also much different compared to those monitored on the field. It was reported by [9] and [11] that the application of one-dimensional consolidation theory using consolidation parameters estimated laboratory tests to under-consolidated clays reasonably estimated the magnitude and rate of consolidation settlement. Conversely, [6] obtained results that support the findings of this study which showed the CPTU method can predict the magnitude of settlement better than the laboratory-calculated estimates using parameters obtained from the consolidation tests. Meanwhile, the striking difference in these results was believed to be due to the lack of consolidated data. The prediction settlement ratio graph generated from the empirical formulation and settlement from the monitoring field is, presented in Figure 8.

The field observations with settlement plates and extensometers were actual and undisturbed to ensure the correctness of the results but laboratory tests such as Cc, LL, including the void ratio, have the ability to change from undisturbed to disturbed and this usually invalidates the results. Therefore, a difference in the theoretical settlement calculations and field observations is considered reasonable and believed to be caused by the Cc factor and one or more several other factors such as the a) invalidated laboratory test results due to the changes in soil conditions from undisturbed to disturbed caused by the condition of the test object, laboratory assistant performing the test, and condition of the equipment b) inaccurate input of data including Cc, void ratio, the thickness of the compressible layer, overburden pressure, and applied stress above the ground level, c) consideration of the soil layer as homogeneous or bilayer when it is practically heterogeneous, d) disturbances in the field which causes inaccurate reading, and e) soil saturated and unsaturated conditions.

Furthermore, a 1-dimensional consolidation equation was formed based on the thickness of the soil layer and void ratio. This made the amount of compression using the Cc empirical formula based on the void ratio to have a value close to those monitored on the field. It is also important to note that the void ratio value in the liquid limit condition, was different from the value in the original condition. in contrast, the pore space between aggregates and particles in LL conditions was found to be larger , and the same was recorded with the water content value to avoid the reflection of the actual condition of the soil layer in the Cc results. Moreover, several tests were used to correlate Cc and LL, such as Oedometer Consolidation, Atterberg Limit, and Volumetric & Gravimetric to ensure a more significant possibility of being wrong or less precise. This means the error probability in finding the Cc vs LL correlation was relatively greater than for Cc vs e.

The results obtained from Figure 8 show that the settlement result using Bowles (1989) method is closest to the settlement plate results when compared to other empirical methods used in this study. This can be seen from the settlement prediction ratio which tends to be low and is close to 1. The results are then used to analyze the confidence level of the data. At the 90% confidence level, the settlement prediction ratio between the empirical formulation using the Bowles method and settlement plate readings ranged from 0.5 to 1.2. Meanwhile, the compression ratio based on the results of study ranged from 0.64 to 1.1. These results are in the coverage of the ratio at the 90% confidence level. Thus, the settlement ratio of settlement using Bowles empirical method and settlement plate based on field data for this study has a confidence level of 90%.

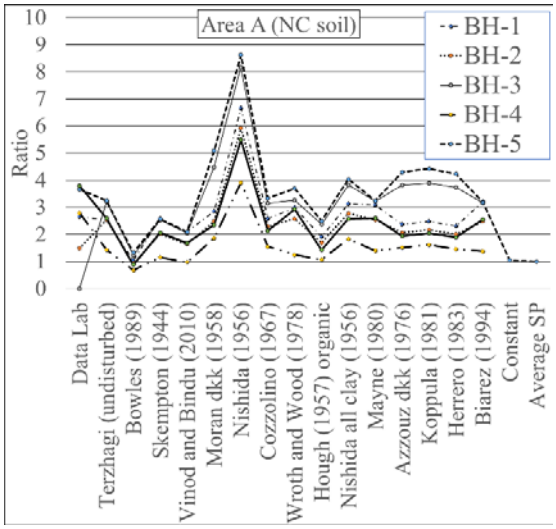

Fig 8a. Settlement prediction ratios generated from the empirical formulation and settlement from field monitoring (Area A)

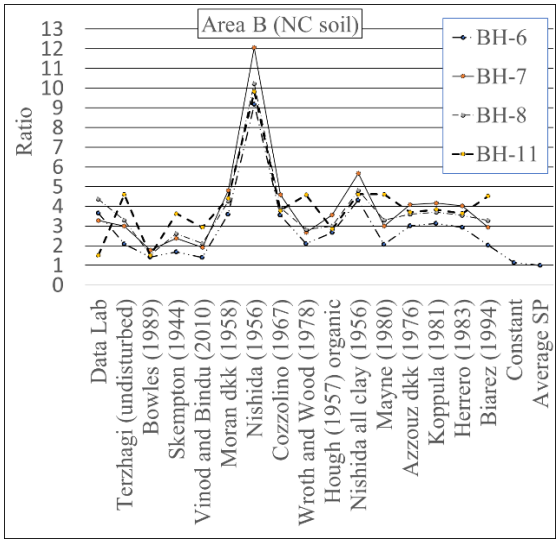

Fig 8b Settlement prediction ratios generated from the empirical formulation and settlement from field monitoring (Area B)

6. CONCLUSION

Determining the parameters for calculating soil settlement is considered complicated and expensive, besides being time consuming. Therefore, there are many empirical formulas to obtain compression parameters, especially the compression index (Cc) parameter. There is, however, a problem of determining the empirical compression index formula to be selected among several formulations developed. Therefore, this study was conducted to compare the compression index with different formulations and determine the most suitable for the settlement of the monitoring field. It was discovered that:

Compression analysis which has the closest soil compaction results with those in the field was the Cc calculated using Bowles (1989) (0.156.eo)+0.0107. This formula was found to be effective in most of the soil data collection points under both NC and OC soil assumptions. Most unreasonable compression was with Nishida's formula (1956) (1.15 (eo-0.35) with the Cc data obtained from lab test found to be unreasonably high due to the lack of consolidated and other supporting parameters which led to the use of too much correlation data.

This means it is necessary to have complete soil compression and other important data parameters to obtain accurate calculation results in ensuring the development in the field. Further research still needs to be carried out at different locations and data to emphasize the results obtained from this research

7. ACKNOWLEDGMENTS

This research was supported by Hibah Penelitian Dana Departmen program through the grant provided by non PNBP Institut Technology of Sepuluh Nopember, Surabaya, Indonesia 2020. (No. 1711/PKS/ITS/2020) and PT Teknindo Geosistem Unggul.

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