A Case Study of Assessing the Accuracy of Secondary Consolidation Prediction Using Qualitative Approach

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ABSTRACT

Infrastructure constructed, especially over soft organic soil layers, can be subjected to excessive settlement within its life cycle due to the complex behaviour of the soft soil with time. However, with necessary actions prior to construction, the impacts from such soil layers can be mitigated to some extent. The case under consideration is a leisure resort in Matara, a 15-storey hotel resting on a raft foundation near the southern coastal line of Sri Lanka. With time, some cracks have formed within the building, and an investigation was done to identify the cause for the crack formation. It has been determined that cracks have appeared due to the excessive settlement of the subsurface. Furthermore, ground investigation results suggest that a peat layer is beneath the building within a depth of 15-24m. As per the survey report on the settlement of the building, secondary consolidation of the soft soil significantly impacts the excessive settlement. Therefore, three methods were used to predict the secondary consolidation settlement of the peat layer beneath the building. The methods are prediction using empirical correlations, laboratory experiment results that will follow the constant coefficient of secondary consolidation throughout time and the qualitative method, which assumes that the secondary consolidation coefficient varies with time. Based on the above techniques, predictions were made, and results suggest that the qualitative method has a significant accuracy compared to the actual settlements of the building. These observations provide some proof that the coefficient of secondary consolidation varies with time according to the qualitative approach and does not remain constant throughout the lifespan of the building as suggested by conventional methods.

KEYWORDS: *Coefficient of secondary consolidation, Crack formation, Settlement, Soft soil, Time-dependent settlement*

1 INTRODUCTION

Organic soil is an important soil type formed by the accumulation of partially or fully decomposed organic matter, such as animal and plant residues. Generally, organic soils have a high amount of moisture contents, high compressibility, and a high rate of creep behaviour properties that result in catastrophic settlements due to increased stresses compared to the other types of soils.

The secondary consolidation settlement is defined as the increase of the settlement due to the reorientation of soil particles under constant effective stress. The primary and secondary consolidation settlements could take place at the same time, but for convenience, it is assumed that only after the completion of the primary consolidation settlement the secondary consolidation settlement begins. Even though the secondary settlement is approximately negligible for sandy and gravel soils, according to Mesri et al. (1997), secondary consolidation settlement is significant for organic soils.

The building under consideration is a 15-storey building constructed on a raft foundation near Weligama in 2012. The building was built with a beach frontage of 115m and a frontage of 100m to Galle Road. The construction is located closer to the coastal area and surrounded by the Polwatta river, as shown in Figure 1.

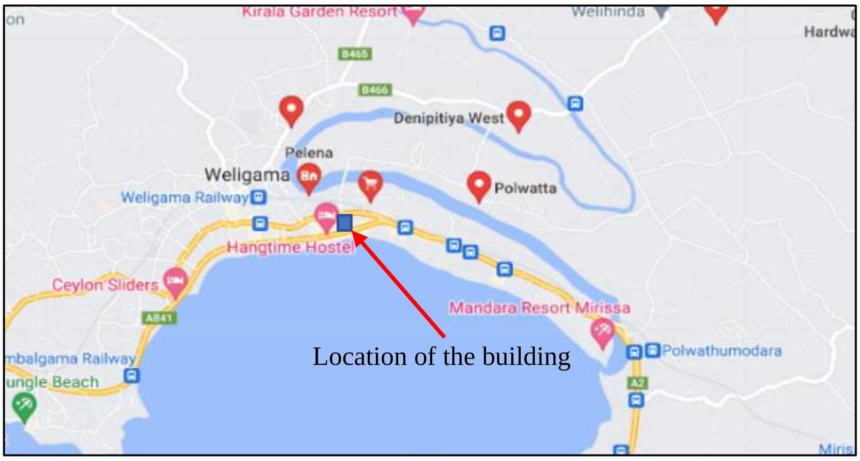

Figure 1. Location of the Leisure Resort

In 2020, significant cracks appeared on the building, eight years after the commenced date. An investigation was conducted to determine why the cracks appeared, and it has been identified that cracks have appeared due to the excessive settlements of the subsurface. During the investigation, the settlement and crack propagation magnitude was measured by establishing serval survey points along each level of the building, as shown in Figure 2.

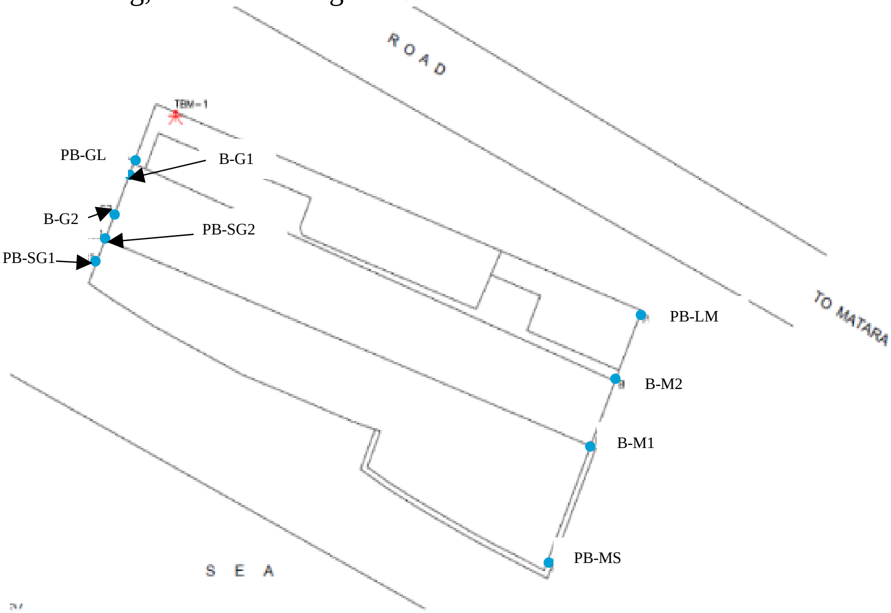

Figure 2. Survey points located at the Ground/Basement level

The survey results show that the building has settled differentially from the sides of the building within a 2-year time. Observed results suggest that the excessive settlement of the building may be due to the secondary consolidation of the cohesive organic soil at its normally consolidated stage underneath the foundation at 15-24m depth below the foundation. Therefore, it tends to settle under the secondary consolidation of soft soil. Even though the conventional method assumed that the coefficient of secondary consolidation under the normally consolidated stage remains constant and does not vary with time, the actual settlements show a progressive increase, and it suggests that C_α varies with time.

The Time-dependent secondary consolidation under the over-consolidate stage was analyzed by Mesri et al. (1997) with the help of special consolidation laboratory test results on a peat sample of Middleton. Observations from the laboratory tests suggest that soft soil (Organic soils) tends to undergo secondary consolidation under the over-consolidated stage with time due to the presence of organic matter. The obtained results of Mesri et al. (1997) were further verified by Ajlouni et al. (2001) on a peat sample of James Bay peat and inorganic clay samples. In both cases, the C''_{α}/ C_{α} ratio increases with the time ratio; however, the pattern is different for Middleton and James Bay peat. In Middleton peat, the C''_{α}/ C_{α} ratio increased with time and slowly reduced. However, in James Bay peat, a gradually increasing trend over time is shown in Figure 3.

Colombo Katunayake Expressway is an example of construction built over an organic soil layer under the soil's over-consolidate state. The consolidation tests done on the organic soil of the CKE project suggest that time-dependent secondary consolidation will occur under the over-consolidated stage. It means with time, organic soil will settle according to the variation of the secondary compression index under the over-consolidate stage.

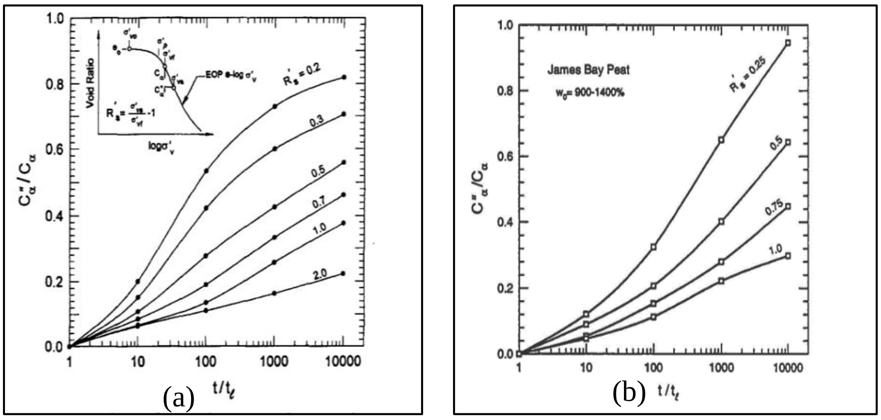

Figure 3. C''_{α}/ C_{α} variation with t/t_l (a) Middleton Peat and (b) James Bay Peat

However, the progressive settlement of the leisure resort in Matara suggests that the normally consolidated organic soil underneath might also be experiencing a similar type of variation in the coefficient of secondary consolidation. Therefore, it is speculated that the above behaviour of over-consolidated soft soil is also applicable to the normally consolidated soil. Parallel to the survey on settlement monitoring of the building, a ground investigation work was done on 6 boreholes near the corners of the existing building as shown in Figure 4, to investigate the soil profile beneath the building and to identify the root cause for the excessive settlement.

Figure 4. Boreholes for the Ground investigation

In this study, the actual settlement of the building will be compared with the predicted settlement of the underlying soft soil layer in two main approaches; (1) considering the coefficient of secondary consolidation (C_{α}) is constant throughout the time and (2) considering C_{α} varies with the time by utilizing the laboratory test results and previous literature. Under the two approaches, three methods have been used; (1) Prediction using empirical correlations, (2) Prediction using laboratory experiments (3) Qualitative method.

2 METHODOLOGY

The coefficient of secondary consolidation should be determined prior to the prediction of secondary consolidation settlement of soft soil. The following sections explain the different methods followed in determining the coefficient of secondary consolidation.

2.1 Coefficient of secondary consolidation is constant throughout the time

- C_α predicted using empirical correlation,

Under this method, the empirical correlation proposed by Vidurapriya et al. (2021) on C_α/C_c for Sri Lankan peats in the southern part was used to obtain the C_α parameter to predict the secondary consolidation settlement using the following equation 1.

$$S_S = \frac{C_\alpha}{1+e_0} HxLog(\frac{t}{t_p}) \quad (1)$$

$$C_\alpha = 0.0331C_c \quad (2)$$

Where S_s – Secondary consolidation settlement, H – Thickness of the peat layer, C_α – Coefficient of secondary consolidation under the normally consolidated stage, t – time considered after completion of primary consolidation, t_p – time of completion of primary consolidation, e_0 – Initial void ratio and C_c – Compression index.

- Constant C_α obtained using laboratory experiments,

Laboratory experiments were conducted on undisturbed organic soil samples that have low organic content extracted from the ground investigation beneath the building. Special consolidation tests were carried out on these samples to investigate secondary consolidation behaviour. The obtained C_α is shown in Table 3 under section 3.1.

2.2 Coefficient of secondary consolidation varies with the Time

According to the observed settlement variation of the building, the actual settlement is increasing rapidly with time, as shown in Figure 5. It suggests that the coefficient of the secondary consolidation does not remain constant with the elapsed time, and it should vary with the time to obtain a rapidly increasing settlement. According to the obtained results from the laboratory tests conducted on undisturbed samples beneath the building, under the over-consolidated state of organic soil, the coefficient of modified secondary consolidation (C'_α) varies with time, as shown in Figure 6. Modified secondary consolidation of organic soil refers to the secondary consolidation that occurs at a reduced rate due to over-consolidation. Therefore, to compare the actual settlement with the predicted settlement, it was assumed that C_α under the normally consolidated state also varies with the time analogues to the over-consolidated state. This method is further explained in section 2.4 and graphically shown in Figure 9.

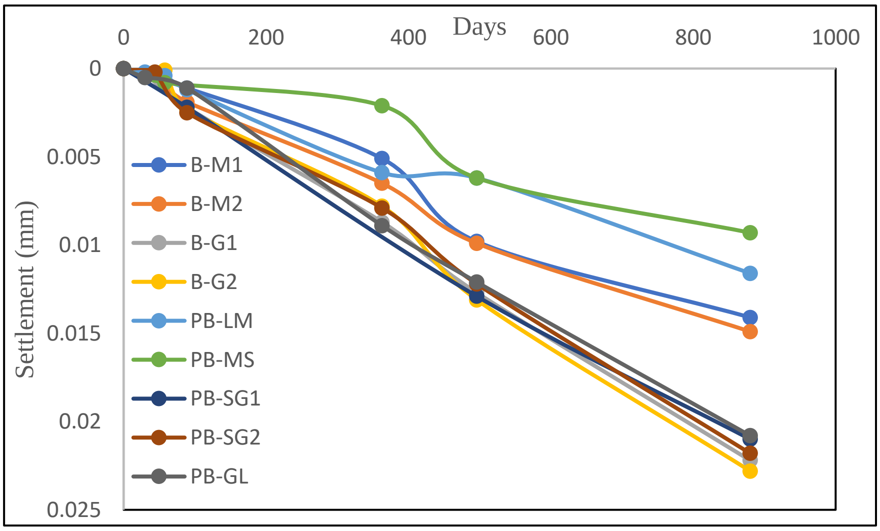

Figure 5. Settlement variation at the ground level of the building

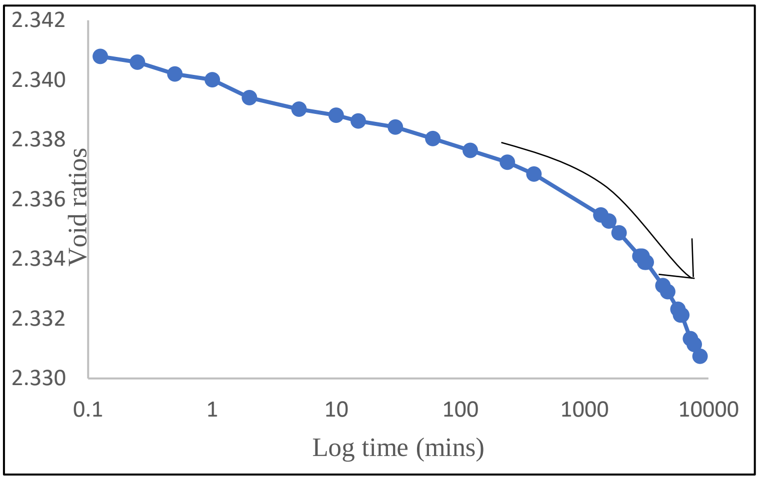

Figure 6. C'$_\alpha$ variation with time under the over-consolidated stage

2.3 Available data

According to the survey conducted on the investigation of cracks appearing in the building, following data was obtained.

- Settlement readings of survey points established along the sides of the building
- Ground investigation data (Subsurface profile) and laboratory test results

Based on the above data, settlement readings of the ground floor level of the building were considered for the convenience of comparison with the predicted settlement readings. The selected ground-floor survey points of the building are shown in Figure 7.

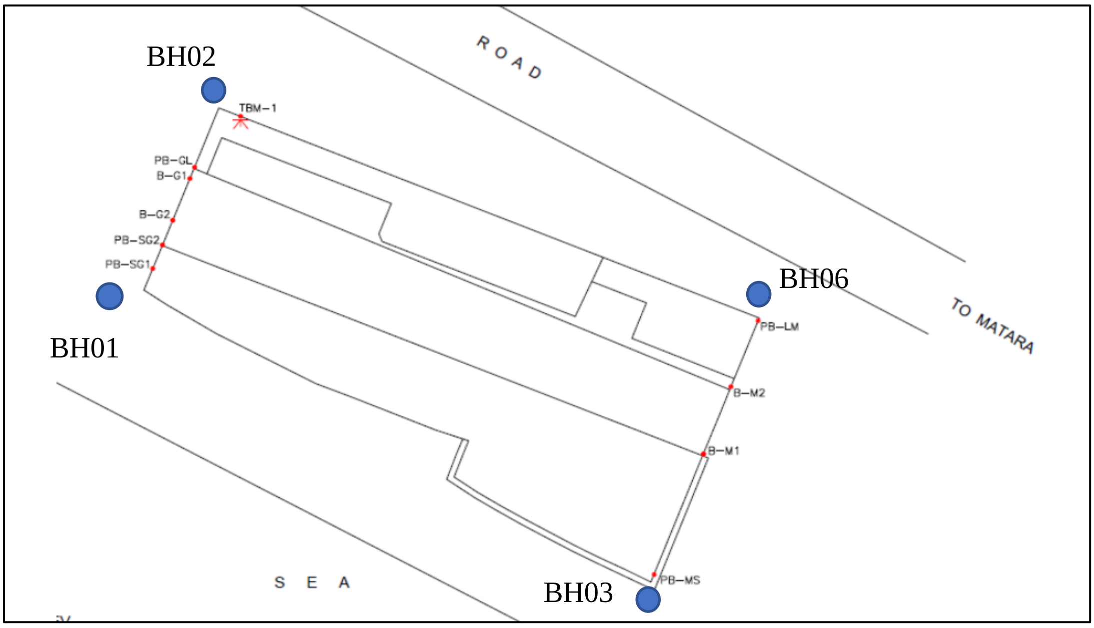

Figure 7. Survey points at the ground level of the building and subsequent boreholes

As the settlement monitoring was done along the edge of the left and right sides of the building, a cross-sectional soil profile was drawn, as shown in Figure 8, using the borehole data to get an approximate layer thickness at the settlement monitoring points, as shown in Table 2. Due to the spread-out survey points of the building, borehole data was assigned to the survey points based on the distance to the borehole location to obtain the average void ratios and C_c values.

- PB-GL, B-G1, B-G2, PB-SG2, PB-SG1 = BH01 & BH02 (Left side of the building from seaside view)

- PB-LM, B-M2, B-M1, PB-MS = BH03 & BH06 (Right side of the building from seaside view)

Obtained void ratios and C_c values for each borehole above mentioned as follows in Table 1,

Table 1. Void ratios and C_c values for the respective boreholes

Borehole	e_0	C_c
BH01	1.996	0.585
BH02	2.237	0.970
BH03	1.713	0.564
BH06	1.674	0.686

Table 2. Layer thickness, average void ratios and C_c values for the survey points

Settlement location	Thickness of the peat layer (m)	Average Void ratios	Average C_c
PB-SG1	6.5	2.117	0.778
PB-SG2	6	2.117	0.778
B-G2	6	2.117	0.778
B-G1	6.5	2.117	0.778
PB-GL	7	2.117	0.778
PB-MS	4	1.694	0.625
B-M1	3.5	1.694	0.625
B-M2	3.5	1.694	0.625
PB-LM	3	1.694	0.625

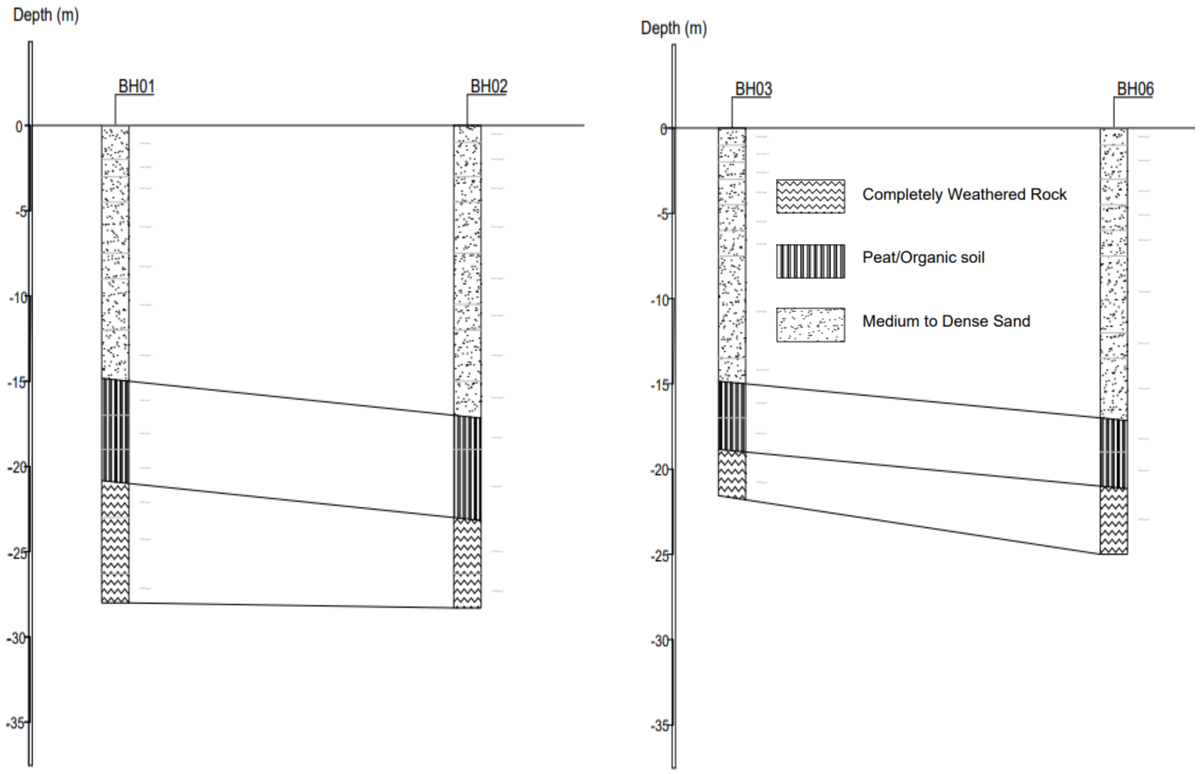

Figure 8. Cross-section profile of the subsurface beneath the Leisure Resort

2.4 Prediction of Secondary Consolidation

Prediction of the settlement at the survey points was carried out as follows,

- C_α constant,
    - Based on laboratory experiments

According to the results obtained through the laboratory experiments mentioned in Table 2. average void ratios and C_α values were considered, and based on equation 1, secondary consolidation was predicted. The following assumptions were made in the prediction of the secondary consolidation settlement.

- Leisure resort construction was commenced in 2012
- Leisure resort construction completion in 2014/06/24
- Assumed that secondary consolidation was appearing in 2014
- Therefore, the End of primary consolidation is 730 days (t_p)

    - Based on the findings of Vidurapriya et al. (2021) on C_α/C_c for Sri Lankan peats

According to the average C_c values mentioned in Table 2 C_α values were obtained with respect to the relationship of $C_\alpha/C_c = 0.0331$. Based on the data mentioned in Table 2, secondary consolidation was predicted using Equation 1.

- C_α varies with the time,
    - Based on qualitative measures of the laboratory results

As discussed in section 2.2, a graph was plotted considering the time ratios and $C_{\alpha m}$ ratios as shown in Figure 9, based on the settlement observations from the special consolidation test results on undisturbed peat samples under the over-consolidated stage.

- Time ratios $= \frac{t_{(n+1)}}{t_n}, \frac{t_{(n+2)}}{t_n}, \frac{t_{(n+3)}}{t_n} \ldots\ldots$
- $C_{\alpha m}$ ratios $= \frac{C_{\alpha m(n+1)}}{C_{\alpha m(n)}}, \frac{C_{\alpha m(n+2)}}{C_{\alpha m(n)}}, \frac{C_{\alpha m(n+3)}}{C_{\alpha m(n)}} \ldots\ldots$

Where t_n = Time considered as a reference value after EOP, t_{n+1}, t_{n+2} = time considered after t_n, $C_{\alpha m(n)}$ = Secondary compression index under over-consolidate stage at Time t_n and $C_{\alpha m(n+1)}$, $C_{\alpha m(n+2)}$ = Secondary compression index under over-consolidate stage at time t_{n+1}, t_{n+2}

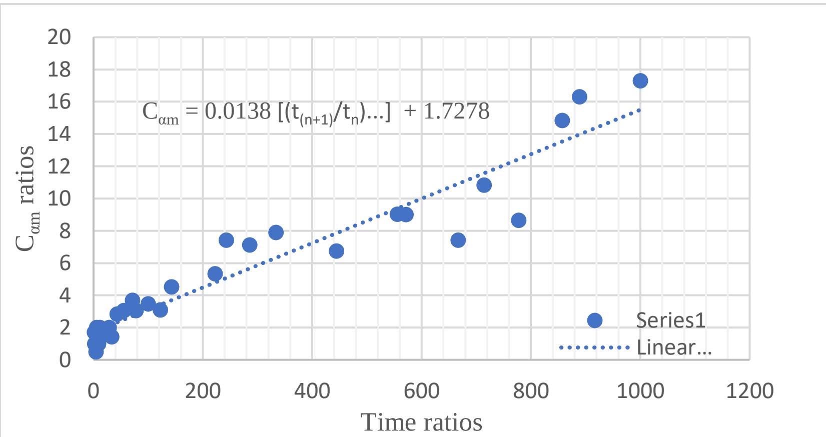

Figure 9. $C_{\alpha m}$ ratio versus time ratio

Based on the above-obtained equation for the plotted graph, C_α values were obtained and by using Equation 1 and data from Table 2. secondary consolidation was predicted.

3 RESULTS AND DISCUSSION

3.1 Organic content of the soil samples and estimated Cα

The following table represents the organic contents and estimated C_α with the help of laboratory experiments under the constant C_α throughout the time.

Table 3. Void ratios and C_α for the tests conducted on undisturbed samples of the leisure resort

Sample No	Organic Content (%)	e_0	C_α
A	27.2	3.927	0.055
B	27.2	3.925	0.056
C	7.2	2.661	0.051
D	5.3	2.36	-
F	8.0	2.316	0.052
Average C_α			0.0535

3.2 Comparison of prediction of secondary consolidation with actual settlement

The comparison of secondary consolidation settlement for the settlement monitoring period is given in a graphical format in figures 10-14.

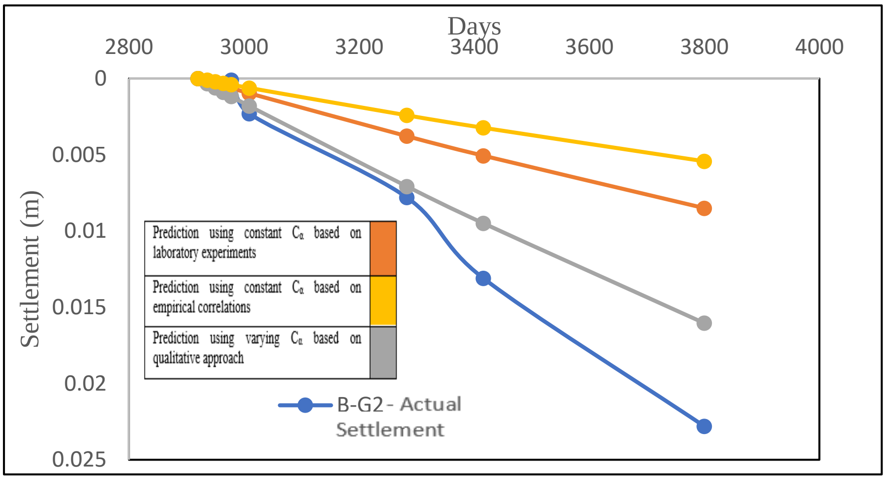

Figure 10. Settlement Comparisosn at B-G2

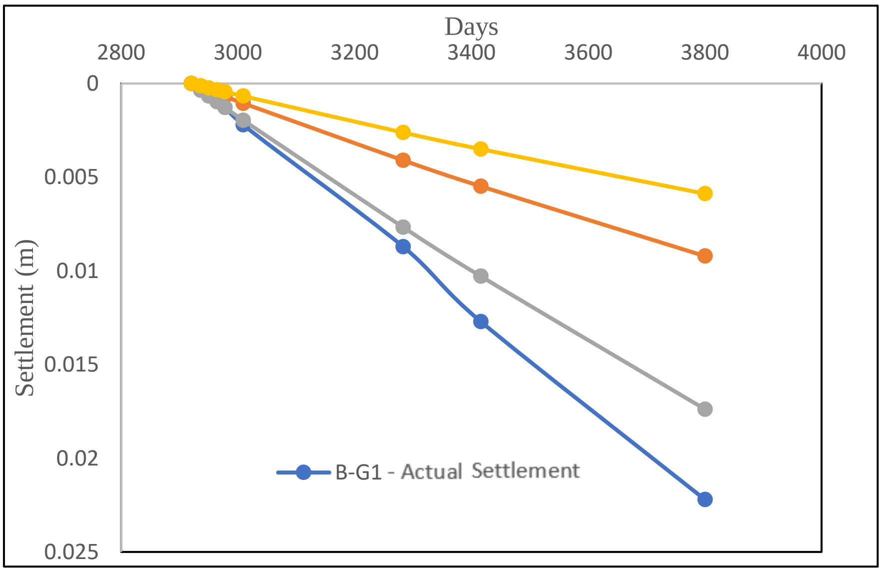

Figure 11. Settlment Comparison at B-G1

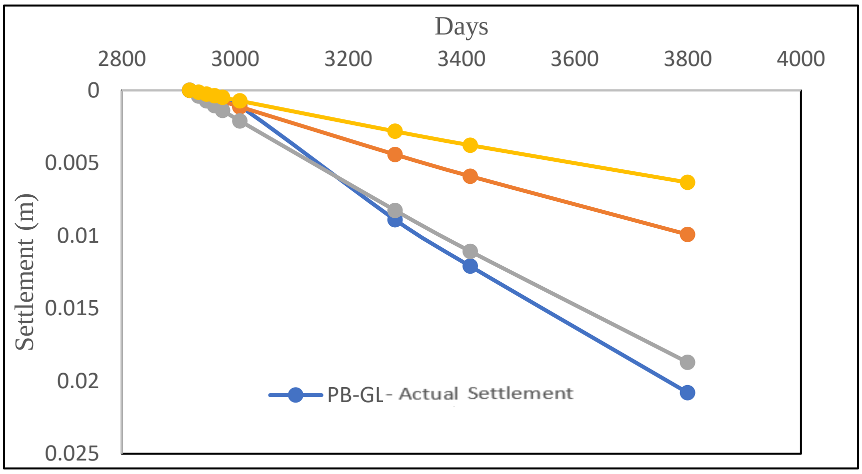

Figure 12. Settlement Comparison at PB-GL

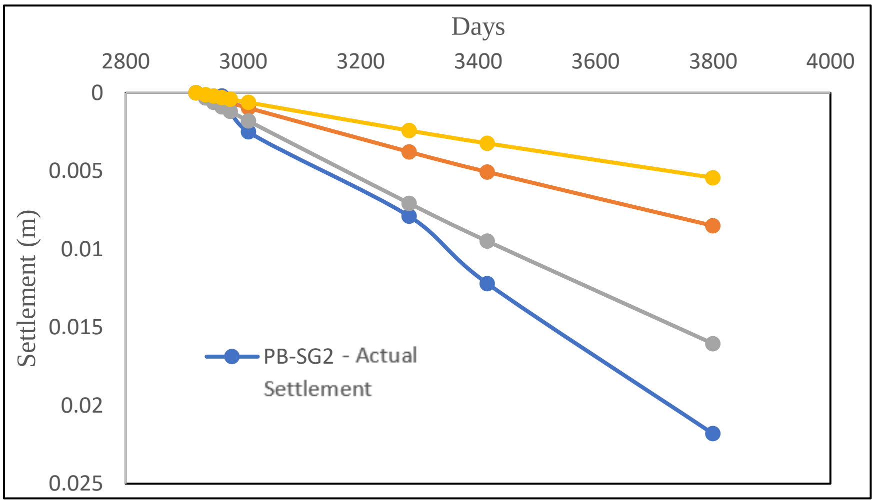

Figure 13. Settlement Comparison at PB-SG2

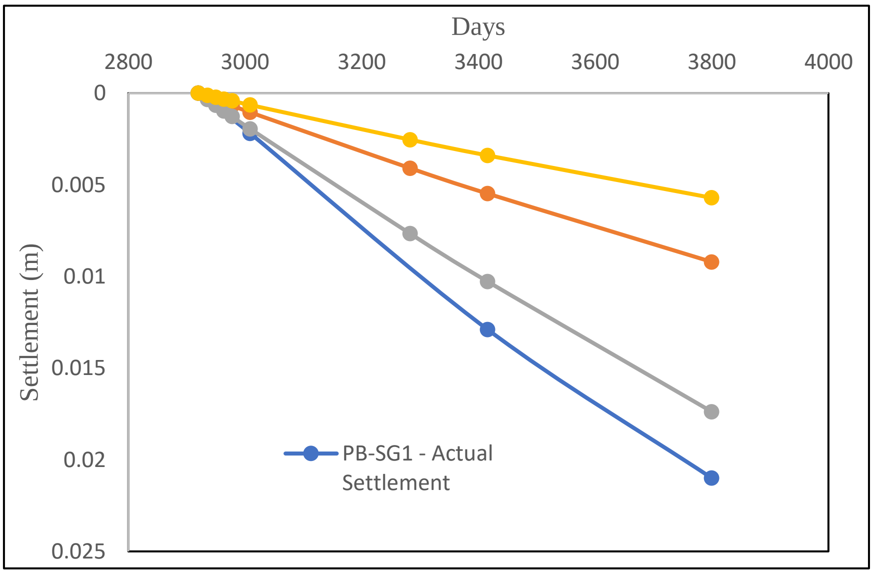

Figure 14. Settlement Comparison at PB-SG1

The graphs suggest that the settlement prediction using C_α obtained from empirical correlation underpredicts the secondary consolidation settlement. The C_α obtained from the empirical correlation slightly varies from the actual C_α values obtained for the soft soil deposit under the building. According to O'Kelly and Pichan (2013), a soil's microstructure significantly affects its physical and mechanical properties. The factors affecting microstructure properties also vary from one deposit to another (Hobbs, 1986; Vasander, 2014). Therefore, the observed underprediction when using empirical correlations can be due to changes in the organic soil's microstructure under consideration. This is further confirmed by the low organic content values as shown in Table 3. under section 3.1, which are typically below the average compared to the other Sri Lankan deposits.

However, as evident from the comparisons above, the prediction of settlement using the actual C_α also does not give accurate results. In most cases presented above, the difference between the measured and predicted settlements gradually increases at a higher rate with the elapsed time. This behaviour suggests that the rate of actual secondary consolidation settlement is not constant, as proposed by the conventional theories used in the industry.

To obtain a better prediction that matches well with the measured settlement, the C_α should be considered a time-dependent variable. Although accurate laboratory experiments should be carried out to determine the variation of C_α with time, only qualitative analysis was conducted in this study due to the lack of appropriate undisturbed samples. The C_α ratio vs time ratio relationship obtained from special consolidation tests on over-consolidated samples extracted from the soft soil deposits under the resort building was used to obtain time-dependent C_α values for the normally consolidated soil. The comparison suggests that the prediction using this varying C_α generates the most accurate settlement compared to the other methods followed in this study. The slight variation observed between the actual and above-predicted settlement could be because these C_α values were obtained qualitatively based on results for overconsolidated soil. To get an accurate settlement prediction, laboratory tests should be conducted to obtain the actual C_α variation with time for these organic soil deposits.

4 CONCLUSION

The secondary consolidation settlement of organic soil deposits is considered more significant than the primary consolidation settlement as it prevails for prolonged periods. Such long-term settlements often cause problems for the long-term performance of infrastructure built on these organic deposits. The resort building considered in this study is an ideal example of such a situation. The excessive differential settlement of underlying organic soil layers, even after eight years since completion, has caused the formation of cracks in the building. The secondary consolidation settlement of the building was analysed using three methods; empirical correlations to predict C_α, C_α determined by a laboratory test and qualitative analysis of time-dependent C_α. Upon successful comparison of settlements predicted using the above methods, it was found that the settlement predicted assuming that the C_α varies with time was the more accurate among the three. This suggests that the C_α of organic soil layers varies with the elapsed time. This study determined the time-dependent C_α by qualitative measures as the data permitted. A systematic quantitative analysis should be carried out to assess the time-dependency of the C_α of organic soil deposits in Sri Lanka to arrive at solid conclusions and more accurate predictions.

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