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Computational Approach for Determining the Variation of Coefficient of Secondary Compression in Secondary Settlement Prediction of Soft Soils

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ABSTRACT

Secondary consolidation settlement takes place in soils after the completion of primary consolidation settlement, which is due to the dissipation of pore water pressure under the applied loads. The secondary settlement usually occurs due to the plastic adjustment of the soil particles and most commonly takes place in organic fine grained soils or soft soils. Hence, it is important to accurately estimate the secondary settlement in soft soils as the final stability of infrastructures built on soft soil grounds mainly depends on the amount of secondary settlement that takes place after the end of primary consolidation settlement. The coefficient of secondary compression (C_α) is a governing parameter in predicting the secondary settlement which is the slope of the consolidation curve for void ratio versus time. Also, various empirical correlations have been found by the past researches to find the value of the coefficient of secondary compression. In most of the instances, the secondary settlement is estimated by considering the coefficient of secondary compression as a constant value. However, the C_α value shows a variation with time and this could affect the secondary settlement estimation. Hence, it is necessary to investigate how the variation of coefficient of secondary compression affects the estimation of the secondary settlement in soft soils.

In this study, the settlement data obtained from the Weligama Bay Marriot Resort and Spa project, Sri Lanka, is compared with the settlement values obtained from a computer generated programme. The progarmme simulates the settlement by considering the variation of the coefficient of secondary compression and by considering a constant coefficient of secondary compression value. The results show that the consideration of varying coefficient of secondary compression (with time) gives more accurate results than considering a constant coefficient of secondary compression in settlement prediction in soft soils.

KEYWORDS: *Secondary Settlement, Primary settlement, Consolidation, Coefficient of secondary compression, Soft soil*

1 INTRODUCTION

Secondary consolidation settlement is the continued deformation in the soil structure that takes place after the dissipation of excess pore water pressure under applied loads (after the end of primary consolidation settlement). Secondary settlement is more significant in clayey soils and in soft soils such as peat but, negligible in sandy soils where only the primary consolidation settlement is significant due to the quick dissipation of pore water pressure under applied loads.

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Soils having an organic content above 75% are classified as peaty soils (Huat et al., 2014). Due to this high amount of organic matter, peaty soil exhibits a high compressibility and moisture content while the shear strength and the bearing capacity is low (Adnan et al., 2007).

The table 1 shows the basic properties of peaty soil based on a research conducted by (Kawa et al., 2019).

Table 1. Basic properties of peaty soils (Kawa et al., 2019)

Index Properties	**Range**
Natural moisture content (%)	414-674
Specific gravity	0.95-1.34
Initial void ratio	7.99-9.64
Fiber content (%)	90.2-90.49
Organic content (%)	88.6- 99.0
Ash content (%)	0.94-11.39
Bulk density (kgm^{-3})	1035.66-1040.41
Linear shrinkage	29.81-30.14
Liquid limit	202.30-220.65

Secondary compression, usually referred as creep, can be expressed by the coefficient of secondary compression Cα, which is a critical element of prediction of long term settlement for designing roads and foundations (Garoushi, 2017). The coefficient of secondary compression can be identified as the slope of the secondary compression on e-log t per load cycle of time (Head, 1986).

Mesri et al., (1973) has stated that for normally consolidated natural soils, the coefficient of secondary compression is influenced by factors such as time, consolidation pressure, precompression, sustained loading, remolding, shear stresses, rate of increase in effective stress, sample thickness and temperature.

They also classified the secondary compression based on the C_α value as shown in Table 2 below.

Table 2. Secondary compression based on C_α % (Mesri et al., 1973)

C_α % (Per log cycle)	**Secondary Compression**
<0.2	Very low
0.4	Low
0.8	Medium
1.6	High
3.2	Very high
>6.4	Extremely high

Many past researches have been conducted to study the variation of coefficient of secondary compression (C_α) with the above factors when estimating the secondary settlement.

Head (1986) found that the coefficient of secondary compression increases with the increment in the vertical effective stress in highly organic clays and in peat. Where, C_α is independent of the vertical effective stress in inorganic clays. In a recent study done by Huayang et al. (2016) on three different soft soil types, it was found that the C_α depends on the vertical effective stress and the initial void ratio. Past research also has been conducted to find the C_α variation with time.

In a study done by Fox et al. (1992), the Compression- log time curves showed that under a constant vertical effective stress value, the coefficient of secondary compression was not constant but increased with Log time. Mesri and Vardhanabhuti (2006) also states that the characteristics of coefficient of secondary compression vary with time. Mesri and Vardhanabhuti (2005), states that as the variation of secondary compression is not constant in Log time and hence, calculating C_α as slope of e – log t pre one cycle of time is not accurate because the slope is changing from cycle to another. In fact, coefficient of secondary compression decreases with time under constant stress in all the cases.

In a research done by Garoushi (2017) on secondary compression of clay soils, he states that the coefficient of secondary compression is directly proportional to the time corresponding to the end of primary consolidation for all loading stages. He also concludes that C_α is not constant with time on Semi-logarithmic scale, instead it decreases. Another conclusion of the study is that an over-estimation of the coefficient of secondary compression in clay soil was observed when calculated from the standard oedometer test results.

However, not much research has been done on considering the variation of coefficient of secondary consolidation with time, in estimating the secondary consolidation settlement. This research focuses on settlement prediction at selected locations in Weligama Bay Marriott Resort & Spa project in Sri Lanka using actual geotechnical parameters obtained from borehole logs and laboratory experiments. The settlement simulation is done for two cases, first, by maintaining a constant C_α value and second, by varying the C_α with time. The settlement variations obtained are then compared with the actual field settlement data in order to identify the accuracy of considering C_α variation in secondary settlement prediction in soils.

1.1 Aim of the research

The aim of the research is to determine the accuracy of considering the variation of coefficient of secondary compression with time, in predicting the secondary consolidation settlement in soft soils.

1.2 Objectives of the research

The main objectives of the research are,

- Simulation of secondary consolidation settlement at selected locations by considering a constant value for the coefficient of secondary compression.
- Simulation of secondary consolidation settlement at selected locations by considering the variation of coefficient of secondary compression with time.
- Comparison of settlement data obtained from the above two methods, with the actual field settlement data.

2 METHODOLOGY

2.1 Selected study area/location

The Marriott Resort & Spa, Weligama is located in the Colombo - Hambantota – Wellawaya road and is a famous holiday destination in Sri Lanka. The construction commenced in the year of 2012 and was open for public on 2014/06/24. By that time, the primary consolidation settlement has completed which is 730 days from the start of the construction. However, by the time an unexpected settlement was experienced by the structure, which was predicted to be an ongoing secondary consolidation. Hence, it was decided to conduct a field investigation which commenced on 4th May 2022 .Six boreholes were marked and Standard penetration (SPT) tests were carried out along with other field/laboratory experiments and the settlement at 8 locations around the borehole areas were measured. Figure 1 shows the aerial view of the investigated area while Figure 2 shows the borehole locations at the investigated area.

Figure 1. Area selected for investigations

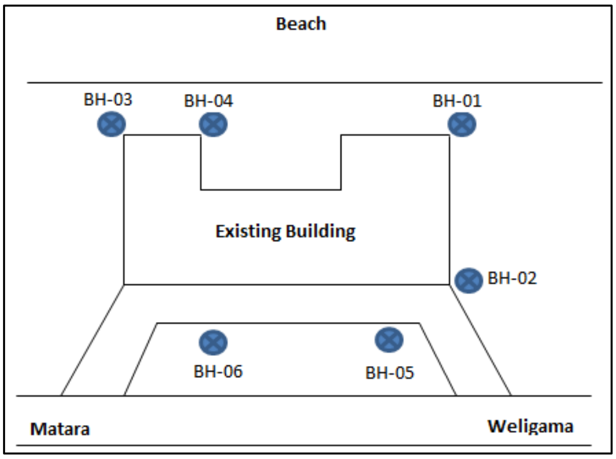

Figure 2. Borehole locations

The ground water table was determined from the measurements taken from an open borehole and found to be fluctuating with rainfall conditions and temperature variations of the area. The settlement monitoring locations are shown in Figure 3 and the soil profile of each location is consisted of a peat / peaty clay layer which confirm the idea of an unexpected ongoing secondary consolidation that is common in peaty soils. Table 3 shows the peaty clay layer thicknesses at various settlement monitoring locations.

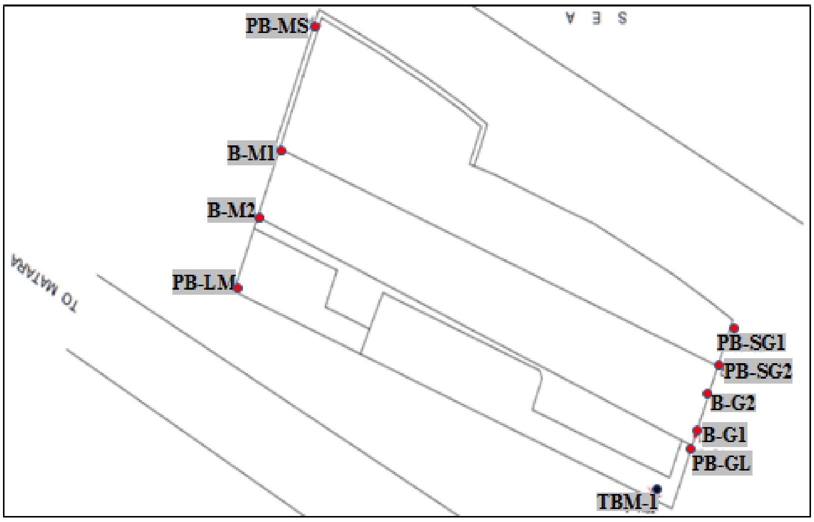

Figure 3. Settlement monitoring locations

Table 3. Peat layer thicknesses at the settlement monitoring locations

Settlement location	Thickness of the peat layer (m)
PB-SG1	6.5
PB-SG2	6
B-G2	6
B-G1	6.5
PB-GL	7
B-M1	3.5
B-M2	3.5
PB-LM	3

2.2 Basic procedure

The data collected from the borehole investigations and the data collected from the field / lab experiments at the settlement monitoring locations, were fed in to a computer generated programme to estimate the secondary consolidation settlement variation at each time interval starting from 2920 days to 3416 days from the start of the construction, which is the duration where the actual settlement monitoring was also carried out.

The settlement simulations were carried out in two different approaches where;

1. A constant coefficient of secondary consolidation was used

And,

2. A time dependent coefficient of consolidation was used.

2.2.1. Approach 01

An empirical correlation has been proposed by Karunawardane (2007) to predict the corresponding C_α values using the respective C_c values for soft/peaty soils in Colombo district, Sri Lanka. Figure 4 shows the empirical correlation proposed by Karunawardane (2007). However, Eq (1) shows an empirical correlation proposed by Vidurapriya et al., (2020) to predict the coefficient of secondary consolidation based on the respective C_c for southern peaty soils. As the soil in the study area is also from the southern part of the country, Eq (1) is used to predict the constant C_α values at each settlement monitoring location as shown in Table 4.

$$C_\propto = 0.0331 C_C \quad (1)$$

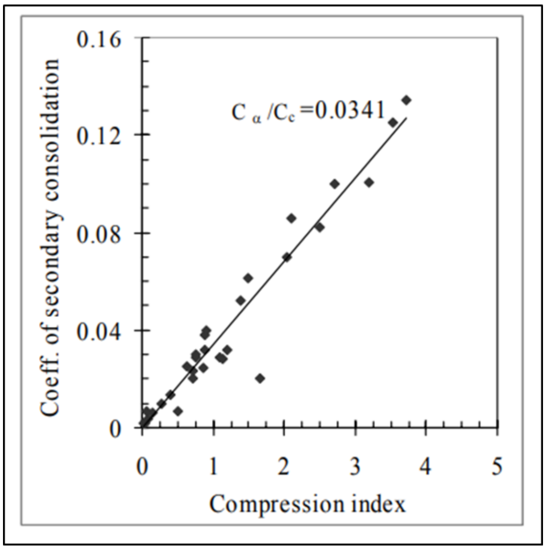

Figure 4. Empirical relationship proposed by Karunawardane (2007)

Table 4. C_α values used in approach 01

Settlement location	**Average C_C value**	**Predicted Cα value**
PB-SG1	0.778	0.02575
PB-SG2	0.778	0.02575
B-G2	0.778	0.02575
B-G1	0.778	0.02575
PB-GL	0.778	0.02575
B-M1	0.625	0.02069
B-M2	0.625	0.02069
PB-LM	0.625	0.02069

The Eq (2) below was used to calculate the secondary consolidation settlement where, S_S = Secondary consolidation settlement, $C_\propto$ = Coefficient of secondary consolidation, H = Thickness of the peat layer, e_p = Void ratio at the end of primary consolidation, t_1 = Time at the end of primary consolidation and t_2 = Time at secondary consolidation. The data shown in Table 2 and 3 were fed in to a computer generated programme as the H values and C_α values respectively, for each location and the e_p vale was also obtained from the respective laboratory results for each location. Parameter t_1 was considered as 730 days which is the time of end of primary consolidation settlement. Parameter t_2 varied from 2920 days to 3416 days with a time interval of 0.2 days in order to calculate the secondary consolidation settlement values at each time interval to obtain more accurate results.

$$S_S = \frac{H\,C_\propto}{1+e_P}\left(\frac{t_2}{t_1}\right) \tag{2}$$

2.2.2. Approach 02

The approach 02 uses the same secondary consolidation Eq (2) and same data as in approach 01 except the C_α.

In approach 02, the C_α varies with each time interval and found by using Eq (3), where, $C_{\propto m\,(n)}$ = Coefficient of secondary consolidation at a given time, $C_\propto$ = Coefficient of secondary consolidation at the end of primary consolidation, $t_{p(n)}$ = The time at which the secondary consolidation settlement is measured, t_p = Time at the end of primary consolidation (Both the times are measured from the start of the initial loading).

$$\frac{C_{\propto m\,(n)}}{C_\propto} = 0.0138\left(\frac{t_{p(n)}}{t_p}\right) + 1.7278 \tag{3}$$

3 RESULTS AND DISCUSSION

The secondary settlement was simulated for 8 locations as discussed in section 2, the settlement variation found by approach 01 (Constant C_α) and approach 02 (Varying C_α with time) are compared with the actual field settlement data obtained for each settlement monitoring location. Figures 5 to 12 show the settlement comparison by considering constant C_α and varying C_α with the actual field settlement variations of all the selected locations.

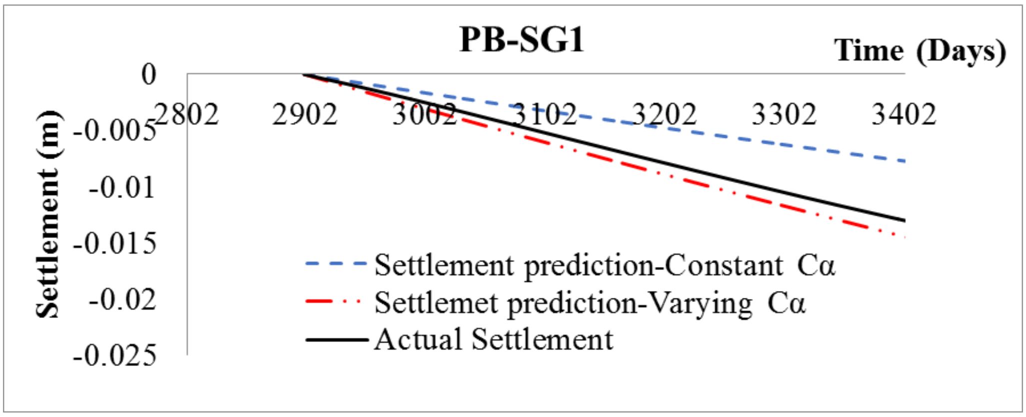

Figure 5. Settlement variation comparison for location PB-SG1

Figure 5 shows the secondary settlement variation at location PB-SG1 where the peat layer thickness is 6.5m. The results show that the secondary settlement is under predicted when a constant value for the coefficient of secondary compression is used and the prediction with a varying C_α is closer to the actual settlement variation. The difference between the maximum settlement values for the constant and varying C_α values is nearly 6.4mm. The difference between the maximum actual settlement value and the maximum settlement value with a constant C_α is nearly 5.1mm while it is only 1.4mm for varying coefficient of secondary compression.

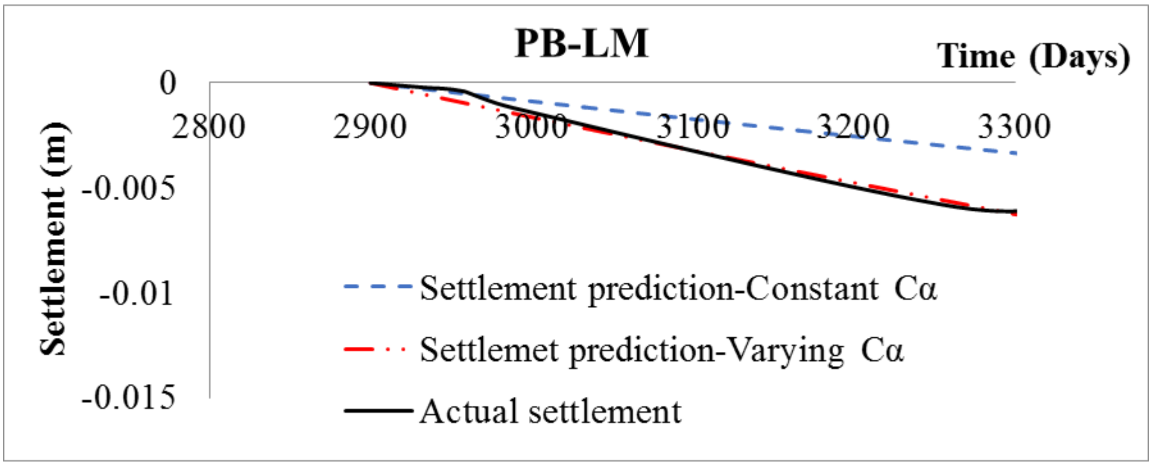

Figure 6. Settlement variation comparison for location PB-LM

Figure 6 shows the secondary settlement variation at location PB-LM where the peat layer thickness is 3m. The results show that the predicted secondary settlement is very low when a constant value for the coefficient of secondary compression is used and the predicted settlement with a varying C_α is almost same as the actual settlement variation. The difference between the maximum settlement value for the constant C_α value and the actual settlement value is nearly 3.3mm.

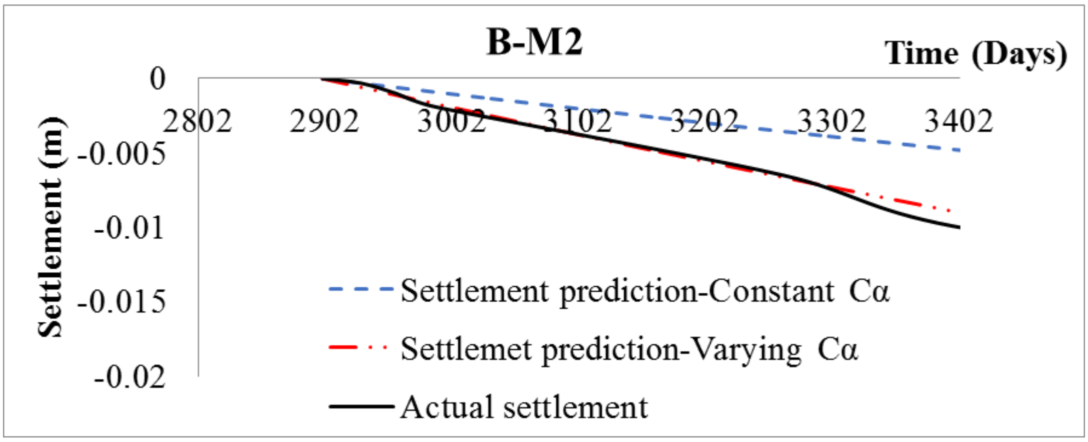

Figure 7. Settlement variation comparison for location B -M2

Figure 7 shows the secondary settlement variation at location B-M2 where the peat layer thickness is 3.5m. The results show that the secondary settlement is under predicted when a constant value for the coefficient of secondary compression is used and the prediction with a varying C_α is closer to the actual settlement variation until 3302 days and then shows a sudden deviation of nearly 1mm. The difference between the maximum settlement values for the constant C_α value and actual settlement is nearly 5mm.

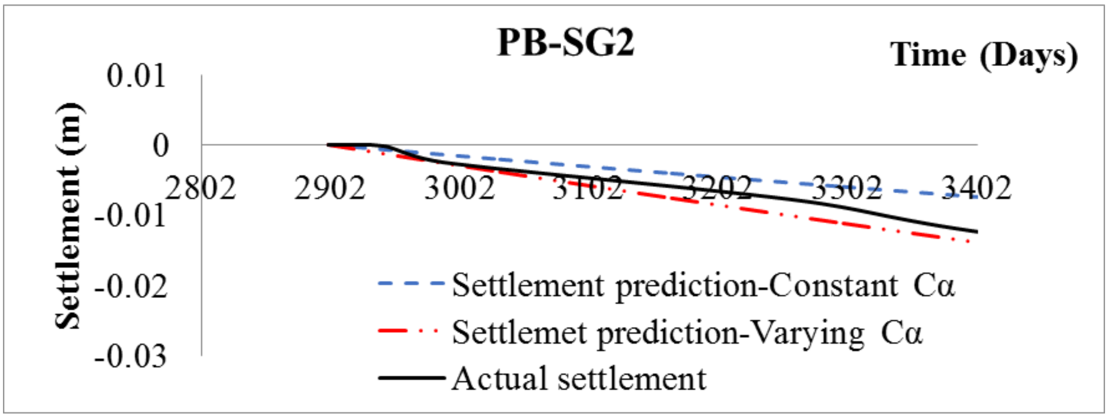

Figure 8. Settlement variation comparison for location PB-SG2

Figure 8 shows the secondary settlement variation at location PB-SG2 where the peat layer thickness is 6m. The results show that the secondary settlement is under predicted when a constant value for the coefficient of secondary compression is used and the prediction with a varying C_α is closer to the actual settlement variation. The difference between the maximum settlement values for the constant and varying C_α values is nearly 6.5mm. The difference between the maximum actual settlement value and the maximum settlement value with a constant C_α is nearly 4.8mm while it is only 1.6mm for varying coefficient of secondary compression.

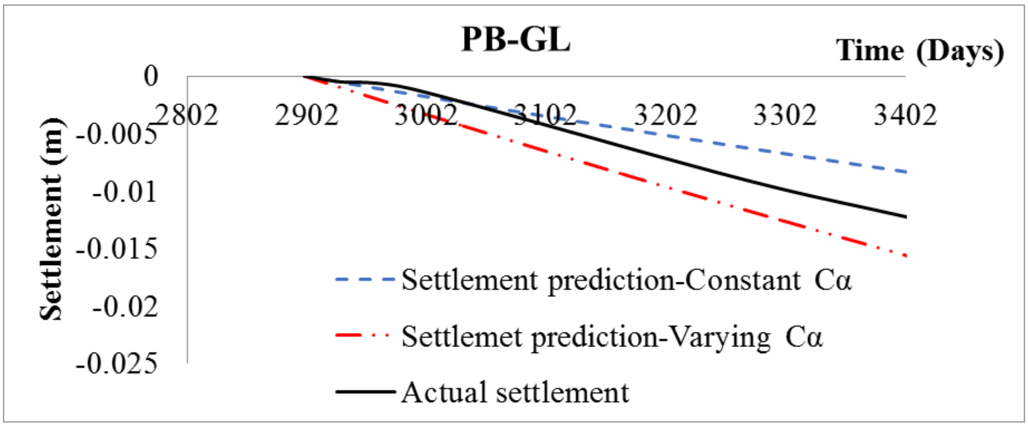

Figure 9. Settlement variation comparison for location PB-GL

Figure 9 shows the secondary settlement variation at location PB-GL where the peat layer thickness is 7m. The results show that the secondary settlement is under predicted when a constant value for the coefficient of secondary compression is used. However, the values for a constant C_α are almost same as the actual settlement until nearly 3100 days. The prediction with a varying C_α is closer, but over predicts the actual settlement variation from the beginning of the period till the end.

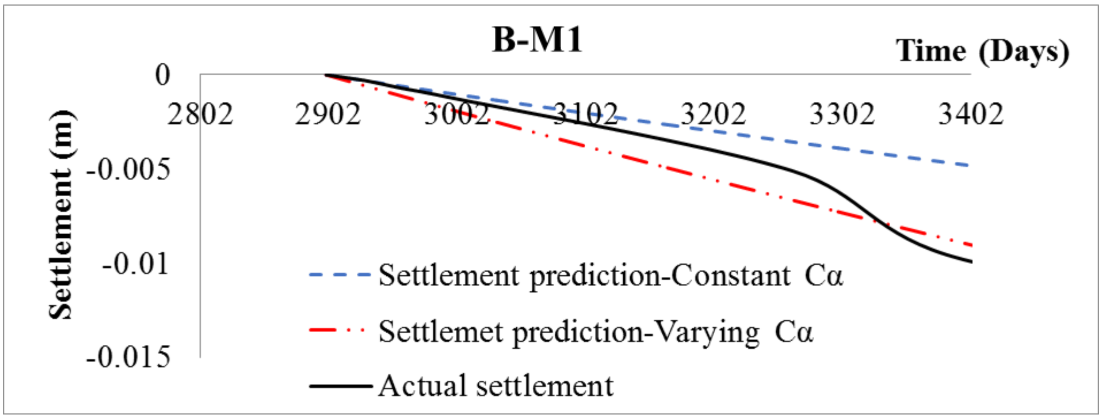

Figure 10. Settlement variation comparison for location B-M1

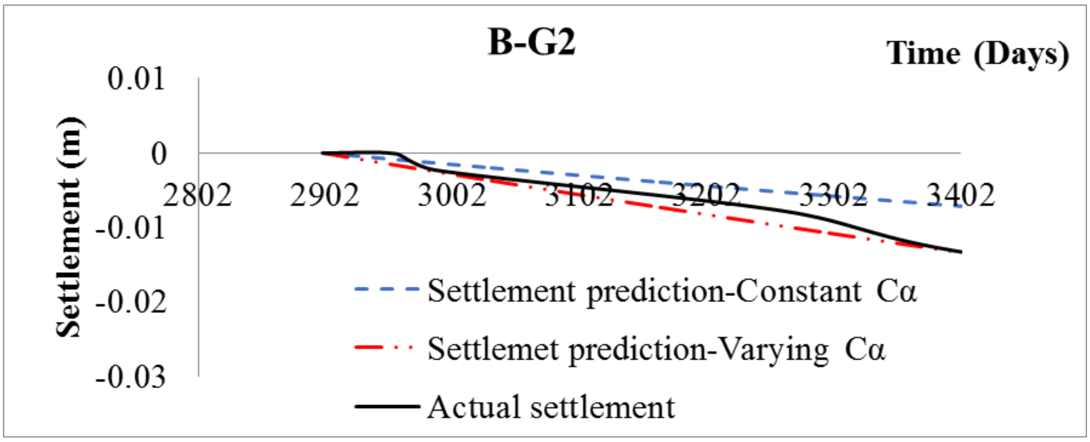

Figure 11. Settlement variation comparison for location B-G2

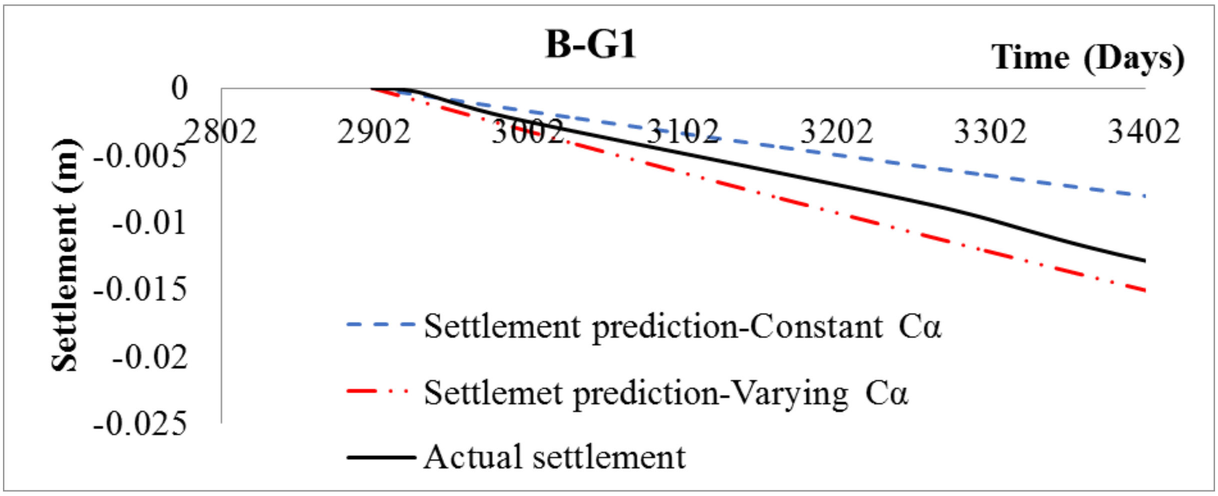

Figure 12. Settlement variation comparison for location B-G1

Figures 10, 11 and 12 show the settlement variations at locations B-M1, B-G2 and B-G1.The secondary settlement prediction with a constant C_α value predicts a settlement that is comparatively very less than the actual field settlement. However, with a varying C_α , the predicted secondary settlement is higher than the actual settlement in these locations. This slight increment could be justified by considering the safety aspects of the locations as the superstructure (Marriott hotel premises) has undergone an unexpected settlement after the end of the construction period (after the end of primary consolidation settlement).

4 CONCLUSION

The actual settlement variation at 8 locations at the Weligama Bay Marriott Resort & Spa project, Sri Lanka, were compared with the settlement predictions obtained from a computer generated programme by considering the C_α variation with time and by considering a constant C_α throughout the time period. The results showed that the settlement predictions were more accurate and closer to the actual settlement predictions when the C_α variation with time, was taken in to consideration while considering a constant C_α would under predict the secondary settlement variation in soft soils. The main reason for this is that the coefficient of secondary compression varies with the varying factors such as ,time, rate of effective stress, consolidation pressure, precompression and sustained loading. Hence, considering a constant value for C_α is not reliable and would give inaccurate predictions for the secondary consolidation settlement values. In this study, for all the eight cases, where the secondary settlement was predicted, the settlement were under predicted when a constant secondary compression value was considered. Therefore, it can be concluded that considering a constant C_α for secondary settlement prediction is unsafe and hence, the consideration of C_α variation with time is recommended in this study.

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