Prediction of Post-Construction Settlement of Road Embankment on Soft Soil Deposits

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ABSTRACT

Organic soils are often considered problematic soils around the world due to several reasons. Excessive settlement is one of the main concerns when constructing infrastructure on soft grounds with organic soil deposits. Ground improvement is mainly carried out on the sub surfaces that lack the strength and stability to bear the structure to be constructed and undergo large settlement during operation. Different soft-ground treatment methods must be applied based on the soil properties to reduce the expected settlements during construction and operation periods. In this context, it is essential to know the behaviour of the subsurface after the ground improvement process. This study mainly investigates the accuracy of the settlement prediction methods during the post-construction stage of the Colombo-Katunayake Expressway Project in Sri Lanka. Settlement prediction was done for the Defect Liability Period using the hyperbolic method, the Mesri method and the Ladd method. A comparison of the predicted settlement with the measured field settlement was done to assess the accuracy of the settlement prediction methods. The comparison showed that the hyperbolic method was more accurate and convenient for predicting the settlement of the embankment.

KEYWORDS: *Soft ground treatment methods; Preloading; consolidation settlement; Asaoka method; hyperbolic method*

1 INTRODUCTION

Ground improvement is done to strengthen, stabilise, and reduce the post-construction settlement of soft soil deposits. Such ground improvement will minimise the unfavourable settlements in the ground that could lead to the serviceability failure of the structure or, sometimes, ultimate collapse. Fine-grained soils with a particularly high degree of saturation and high organic content, such as peat, could be problematic for both stability and the settlement of embankments (Den Haan and Kruse, 2006; Huat, 2006). For several reasons, the secondary consolidation settlement is often considered more significant than the primary consolidation in organic soils. The time taken to complete primary consolidation is shorter in organic soils, and the soil reaches the end of primary consolidation within a short period from initial loading. However, the secondary consolidation settlement prevails for extended periods, and the magnitude of settlement is also considerably high compared to most inorganic soils (Mesri et al., 1997). Therefore, Preloading and other ground improvement techniques mitigate structural failures during the defect liability period by reducing the magnitude of secondary consolidation settlement. It is crucial to accurately predict the secondary consolidation behaviour during this period to facilitate the initial design process and ensure the embankment's long-term performance. Several methods are used to predict the post-construction settlement of organic soil deposits. In this study, the commonly practised prediction methods such as the hyperbolic method, the Mesri et al. (1997) method

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and the Ladd method (Han, 2015) are used to predict the settlement during the defect liability period and to compare with the measured settlement.

In the Colombo-Katunayake Expressway project, from the chainage K0+000 to K25+800 starting from Colombo, the initial borehole profiles indicate the presence of peat layers throughout the length of the section with a thickness varying from 0.5m to 14.2m. The organic soil is mainly concentrated in the first 8km from the direction of Colombo of the expressway (Hsi et al., 2015). Depending on the thickness of the peat layers and the proposed design, different ground improvement techniques such as; Preloading, Preloading with Prefabricated Vertical Drains (PVD), Crushed Stone Piles, Sand Compaction Piles, and Driven Piles have been used to minimise the settlement of the subsurface. Settlement monitoring was conducted during ground improvement at all sections and some sections for a defect liability period of three years to assess the effectiveness of the soft ground improvement due to the application of the techniques mentioned above. A few such road embankment sections were selected for the present study based on data availability.

2 METHODOLOGY

2.1 Test variables

The study primarily focused on embankment sections using the preloading technique, and the locations selected for the analysis are presented in Table 1.

Table 5: Selected sections for analysis with Preloading

Chainage	The thickness of the peat layer (m)	Depth to peat layer (m)
K3+400	1.4	3.5
K7+800	2.2	5.8
K12+150	12.1	4.4
K13+050	1.4	4
K18+800	1.2	2.8
K19+600	1.9	0.6

Figure 1 presents a typical settlement variation with embankment height for selected K7+800 chainage, consisting of an organic layer of 5.8m thickness.

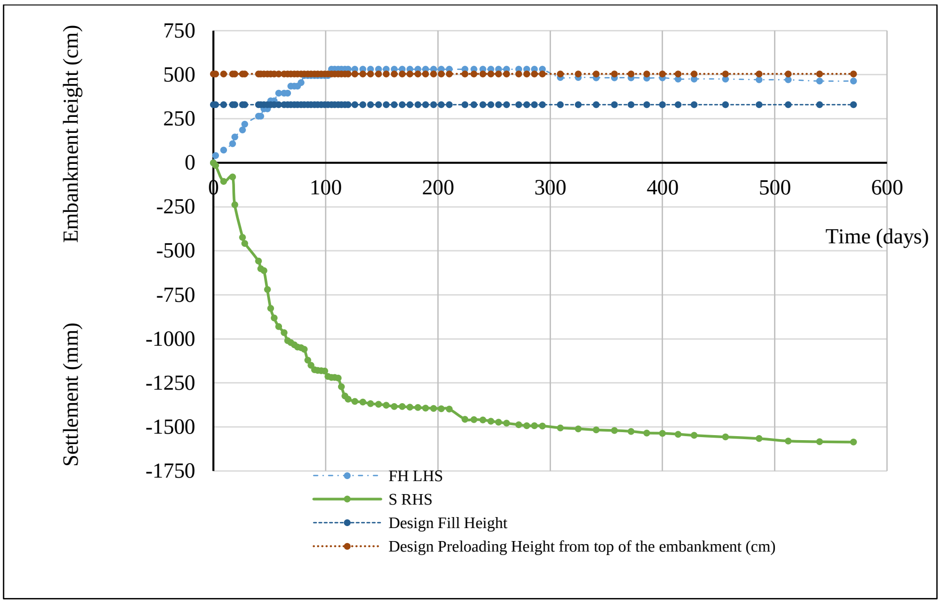

Figure 6: Variation of settlement with embankment height for K7+800

2.2 Applicability of the Asaoka method to field settlement data

Asaoka method is a widely practised settlement prediction method due to its simplicity and ability to determine the end of primary consolidation settlement. (Asaoka, 1978). Asaoka method was applied for the settlement data, where the surcharge loading remained constant, and the end of primary consolidation was obtained. The degree of consolidation attained in the soft soil by the time of removal of the surcharge can be found by determining the end of the primary consolidation settlement.

2.3 Applicability of the hyperbolic method to field settlement data (Tan et al., 1991)

The hyperbolic plot of *t/s* vs *t* for the settlement monitoring data during the construction of the embankment was plotted, and the parameters α and β were obtained according to the hyperbolic equation. The settlement was then predicted using the hyperbolic relationship.
The hyperbolic equation in Equation 1 was used to predict settlement at a required time during Preloading.

$$\frac{t}{s} = \alpha + \beta t \tag{1}$$

Where t is the time of the settlement s is observed, and α and β are constants obtained from the hyperbolic plot of the respective test location.

2.4 Secondary compression based on the Mesri method

Mesri et al. (1997) developed a relationship between C_α'/C_α to determine the secondary compression settlement after surcharge removal. Mesri method can determine the secondary compression index after surcharge removal and the secondary settlement. (Mesri et al., 2001)
Mesri method was applied to determine the secondary settlement after the surcharge removal. C_α'/C_α values cannot be obtained for R values less than 0.2 from the Mesri method, which is an explicit limitation of this method.

Figure 2 presents the Mesri curves, which are used to determine the C_α'/C_α ratio and thereby C_α', the modified secondary compression index.

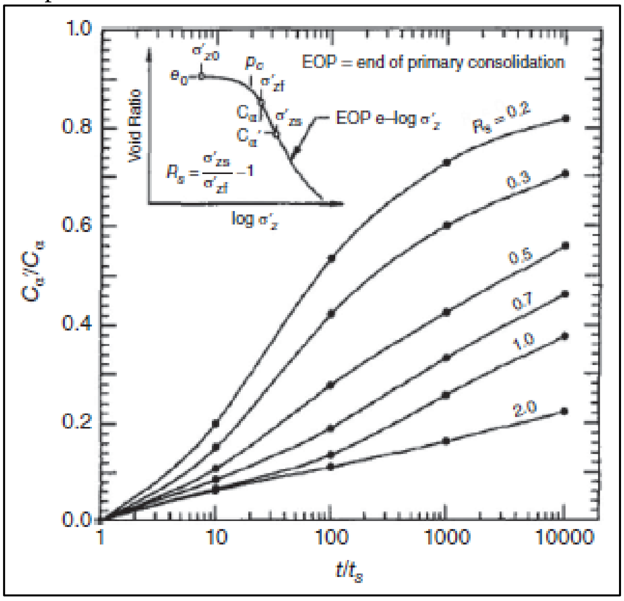

Figure 2: Mesri graphs for C_α'/C_α versus t/t_s (Mesri et al., 1997)

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2.5 Secondary compression based on the Ladd method

Ladd method uses a relationship between the Adjusted Amount of Surcharge (AAOS) and C_α'/C_α to determine the modified secondary compression index (Han, 2015). Figure 3 presents the Ladd graphs, which were used to determine the C_α'/C_α ratio and thereby C_α', the modified secondary compression index. The C_α value for the analysis was obtained from the study done on peaty soil by Ariyarathna et al. (2010), as shown in Equation 2.

$$C_\alpha = 0.033C_C \tag{2}$$

Where C_α is the secondary compression index before surcharge removal, and C_c is the compression index.

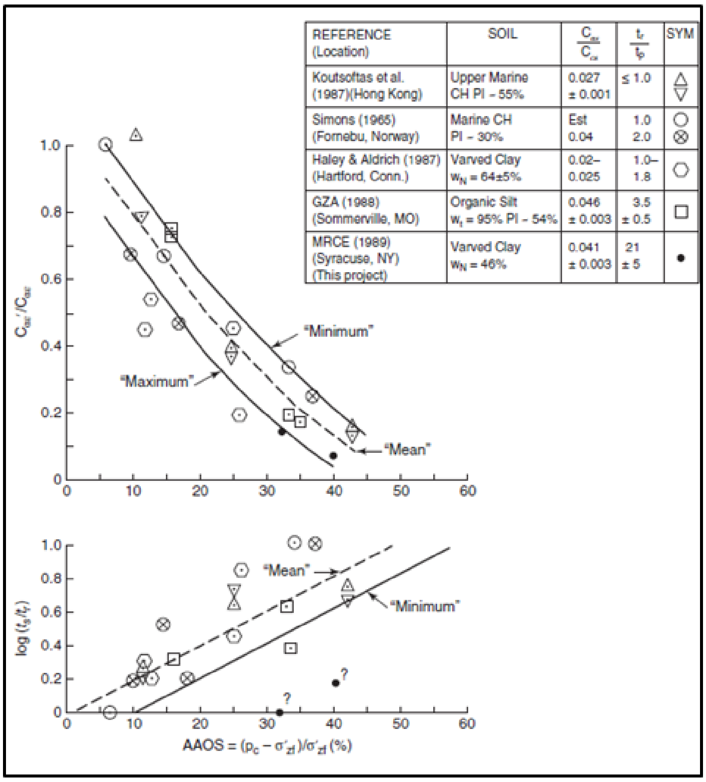

Figure 3: Ladd graphs for C_α'/C_α versus AAOS (Han, 2015)

All the above-stated methods were applied in the determination of the secondary settlement during the construction and service phases.

3 RESULTS

From the application of the Asaoka method on the preloading locations, it was determined that primary consolidation had been completed by the time of removal of the surcharge. The time and settlement data corresponding to the constant embankment load were considered for the Asaoka method application. Figure 4 shows the Asaoka plot for the Left side of the embankment at K12+150 chainage, where k and k-1 are the settlement monitoring data recorded at successive times. The primary settlement obtained by the application of the Asaoka method is presented in Table 2.

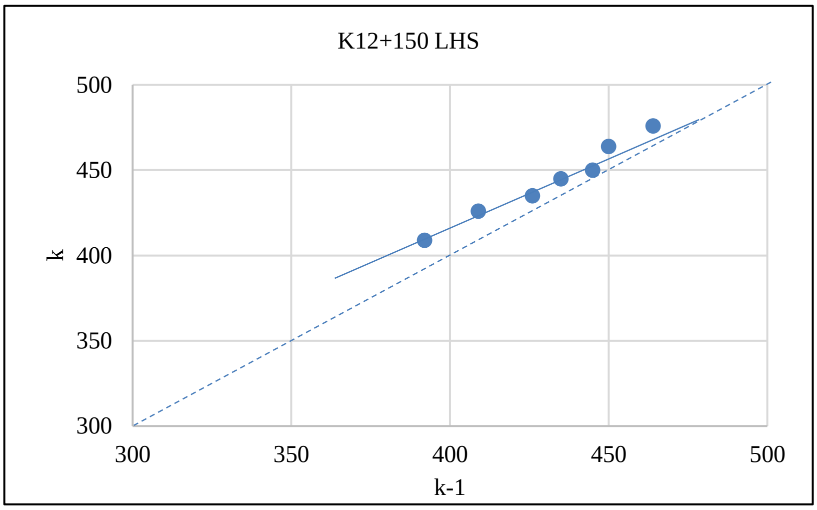

Figure 4: Asaoka plot for K12+150 LHS

Table 2. Primary settlement comparison for preloading locations

Location	Peat layer thickness (m)	Primary settlement (using Asaoka method)		Settlement at the removal of surcharge (mm)		Degree of consolidation achieved (%)	
		LH	RH	LH	RH	LH	RH
K3+ 400	1.4	419	460	423	464	100	100
K7+ 800	2.2	943	1461	978	1494	100	100
K12+ 150	12.1	474	475	484	473	100	99.6
K13+ 050	1.4	407	678	412	686	100	100
K18+ 800	1.2	320	317	312	313	97.5	98.7
K19+ 600	1.9	164	143	162*	140*	98.7	97.9

*Last settlement reading available. No surcharge removal done until the last date of settlement monitoring

The end of primary consolidations was obtained using the Asaoka method, and it was found that the soft soil layer had reached 100% of its primary consolidation by the time of the removal of the surcharge. The hyperbolic plot of *t/s* vs *t* for the settlement monitoring data during the embankment construction was plotted. The predicted settlement was then calculated using the hyperbolic equation and plotted against the actual settlement. Figure 5 shows the results of the application of the hyperbolic plot for the K3+400 chainage.

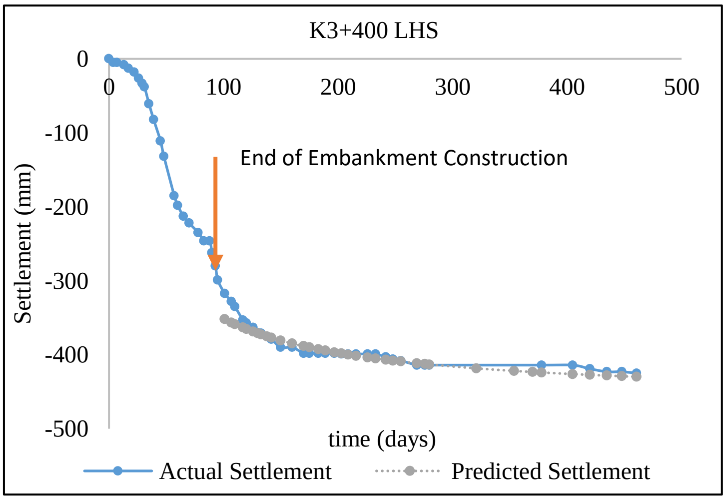

Figure 5: Hyperbolic settlement prediction for K3+400

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According to Figure 5, the actual settlement during the embankment construction stage will closely follow a hyperbolic variation, agreeing with the settlement predicted by the hyperbolic equation. The hyperbolic parameters obtained from the settlement measured during the embankment construction period satisfy the hyperbolic equation; thereby, these parameters will be used to predict settlement in the service period. The secondary consolidation settlement for the service period was also calculated using the Ladd and the Mesri methods after determining the end of primary consolidation. Figures 6, 7 and 8 present the settlement comparisons for chainage K7+800 during the service period obtained using the Mesri, Ladd, and hyperbolic methods.

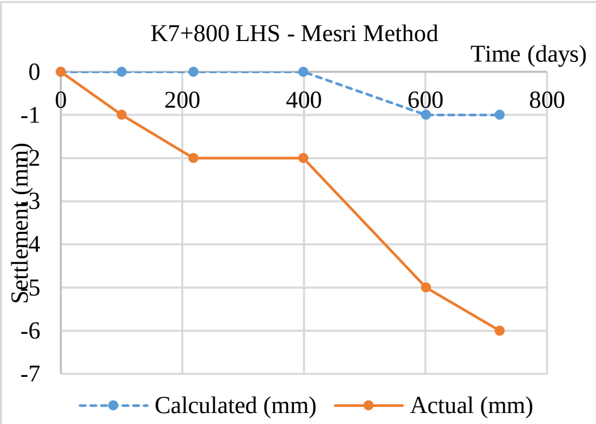

Figure 6: Settlement during DLP using the Mesri method for K7+800 LHS

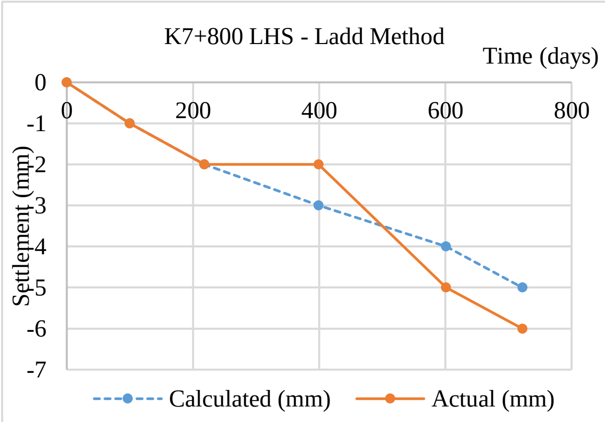

Figure 7: Settlement during DLP using the Ladd method for K7+800 LHS

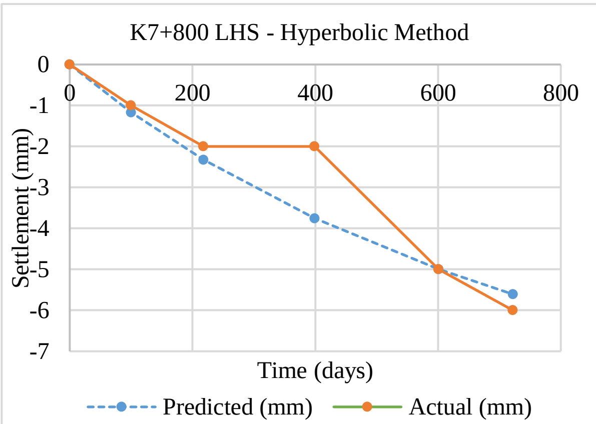

Figure 8: Settlement during DLP using the hyperbolic method for K7+800

4 DISCUSSION

Hyperbolic settlement prediction was more satisfactory for the settlement prediction after the removal of the surcharge load than the other two methods; the Ladd method and the Mesri method. The hyperbolic method was applied to the settlement data for which the constant embankment loading and the hyperbolic equations were obtained. Figure 9 shows the hyperbolic settlement prediction during the embankment construction phase for K12+150 chainage using the hyperbolic parameters obtained during this research. As shown in Figure 9, the variation of the predicted settlement shows similar behaviour to the actual field settlement. Since critical consolidation takes place at the latter stage, at approximately a degree of consolidation of 40% to 90%, the hyperbolic method can be successfully used for settlement prediction during the embankment construction period.

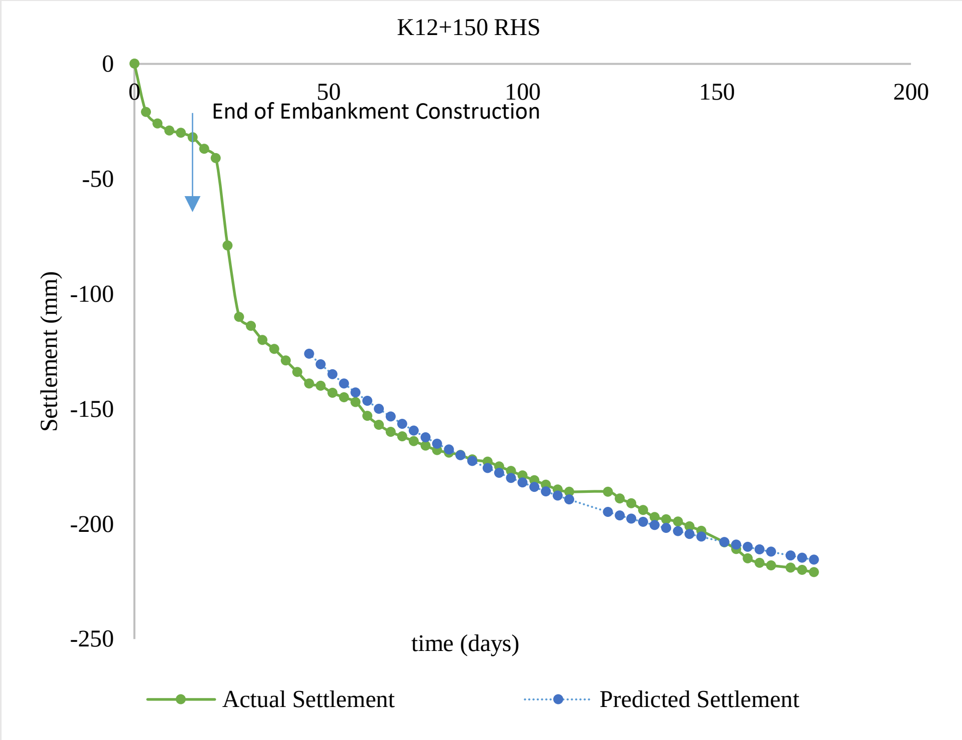

Figure 9: Hyperbolic settlement prediction for K12+150 RHS

Figures 10 to 15 show the settlement comparison for the Defect Liability Period (Service Period) using the three settlement prediction methods where applicable; hyperbolic, Mesri and Ladd methods, against the observed field settlement data for K3+400, K7+800, K12+150, K13+050, K18+800 and K19+600 chainages respectively. Out of these, for chainages K3+400, K18+800 and K19+600, the Mesri method could not be applied as, in the Mesri graphs that are commonly referred to in the industry, the C'_α/C_α variation for R = OCR – 1 values less than 0.2 cannot be found. The lack of C'_α/C_α ratio for soils with lower over-consolidation ratios can be identified as one of the significant limitations of using the Mesri method. Here, $t = 0$ marks the start of the service period.

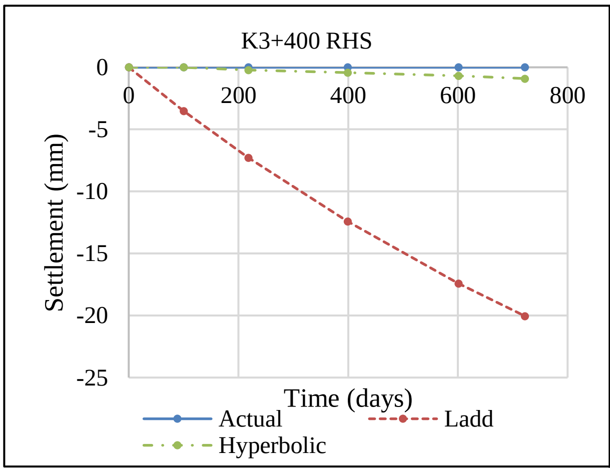

Figure 10: Comparison of Observed settlement values with Predicted settlement values for K3+400

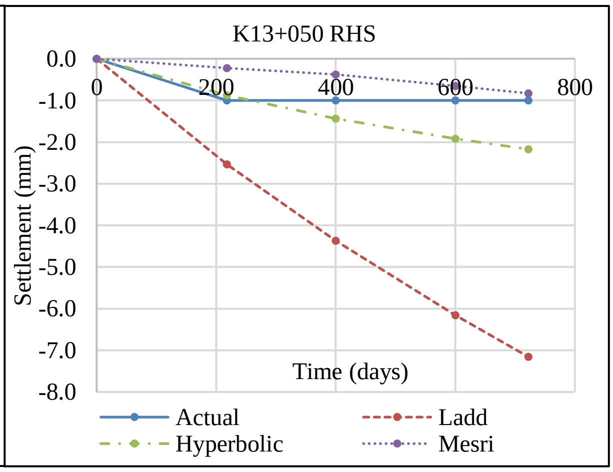

Figure 11: Comparison of Observed settlement values with Predicted settlement values for K13+050

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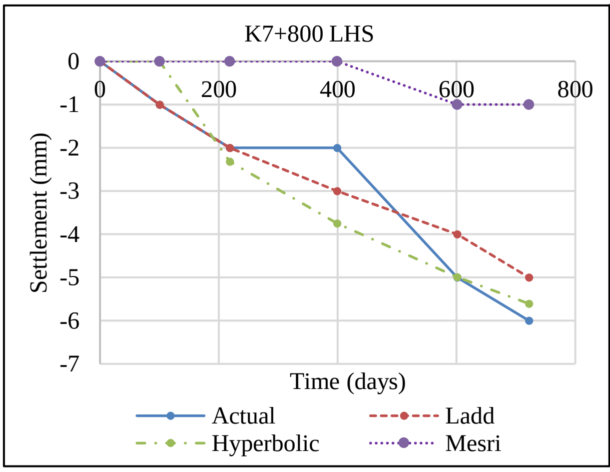

Figure 12: Comparison of Observed settlement values with Predicted settlement values for K7+800

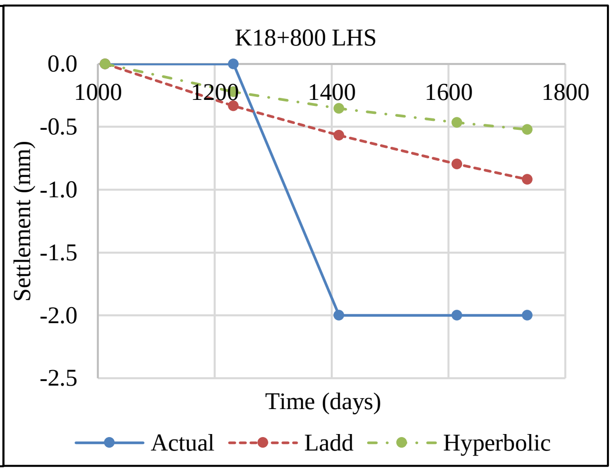

Figure 13: Comparison of Observed settlement values with Predicted settlement values for K18+800

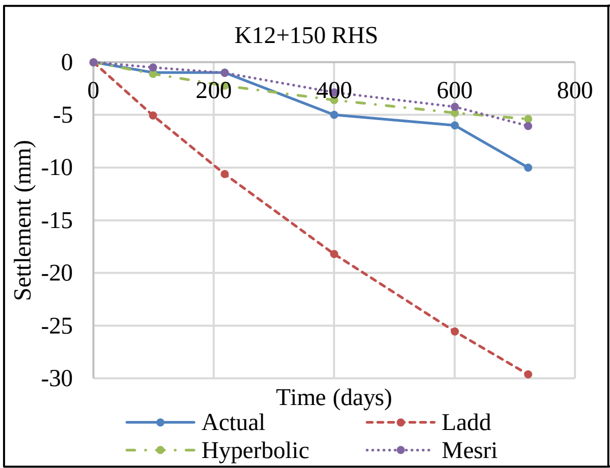

Figure 14: Comparison of Observed settlement values with Predicted settlement values for K12+150

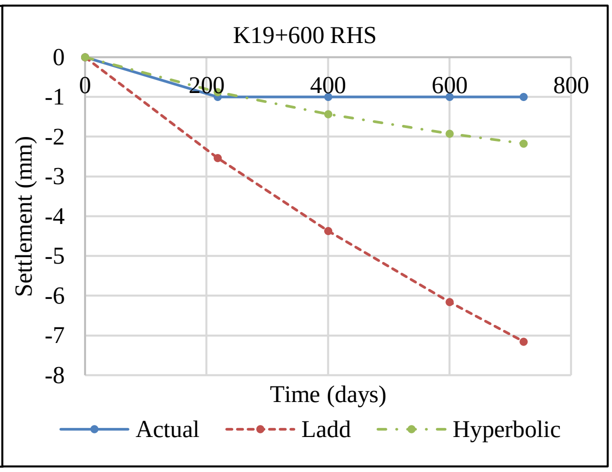

Figure 15: Comparison of Observed settlement values with Predicted settlement values for K19+600

It was discussed earlier in this section that the settlement prediction method based on initial observations could accurately predict the settlement during the preloading stage. Figures 10-15 also show that the most accurate settlement prediction was made using the hyperbolic method, even in the defect liability period. It should also be noted that these hyperbolic predictions were made based on the parameters derived from the settlement monitoring data of the preloading phase. This can be considered an added advantage of the method, as the settlement prediction in the defect liability period does not require additional calculations. In contrast, the Ladd and the Mesri techniques involve a series of calculations to determine the modified coefficient of secondary consolidation after the surcharge removal to predict the settlement.

Mesri method produced the second-best prediction from the settlement comparisons of locations where the method could be applied. Mesri et al. (1997) proposed these curves based on laboratory test results carried out on samples extracted from Middleton peat deposits. According to Hobbs (1986), the properties of organic soils vary drastically from one deposit to another. Though these curves proposed by Mesri et al. (1997) could accurately predict settlement for organic soils with similar properties to Middleton peat, the same accuracy cannot be expected if used on soil with different properties. Hence, by deriving or utilising C'_α/C_α ratio vs time ratio curves for organic soil deposits that match the soil's properties in consideration, more accurate settlement predictions can be obtained. As Mesri et al. (2001) suggest, the C'_α/C_α ratio varies with the elapsed time. However, in the Ladd method, rather than reporting a C'_α/C_α ratio variation with time, a C'_α/C_α ratio variation with the surcharge load was presented. This can be identified as one of the significant reasons for the considerable divergence between the actual settlement and the settlement predicted using the Ladd method.

5 CONCLUSION

The secondary consolidation settlement of organic soil is considered more important than the primary consolidation settlement for several reasons. Due to this reason, the post-surcharge secondary consolidation settlement of road embankments constructed on soft grounds is considered vital for their long-term performance. This paper compared the results of three post-surcharge secondary consolidation settlement prediction methods widely used in the industry with the measured settlement of the Colombo – Katunayake Expressway embankment sections. After determining the end of primary consolidation from the Asaoka method, all six sections considered in this study showed that the primary consolidation had been completed. The degree of consolidation was nearly 100% when the surcharge was removed. Mesri, Ladd and hyperbolic methods were used to predict the post-surcharge secondary consolidation settlement and later compared with field settlement measurements. The comparison demonstrated that the settlement predicted by the hyperbolic method is the most accurate among the three selected methods. As the hyperbolic method adopts an observational method in predicting the settlement, it eliminates the errors associated with the uncertainty of material properties and behaviours. Moreover, the results suggest that the hyperbolic parameters determined in the embankment construction stage can also be successfully used in predicting post-surcharge secondary consolidation. Therefore, the hyperbolic method facilitates convenient and accurate secondary consolidation settlement prediction during the service period.

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