ANALYSIS OF SETTLEMENT MONITORING DATA TO ASSESS THE STATE OF PRIMARY AND SECONDARY CONSOLIDATION OF SOFT ORGANIC SOIL DEPOSITS

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Abstract: Organic soil deposits under road embankments may cause consolidation settlement problems during the serviceability stage. It is not feasible to design road traces on such soil deposits using the traditionally used most unfavourable ground conditions. Instead the most probable ground conditions are used in the initial design and this approach is referred to as the observational approach. The risks associated with using most probable soil properties are managed by reviewing the initial design through the analysis of the observational data obtained during the construction stage. In this regards, analysis tools to assess the stability of the embankment during construction stage and the estimation of the degree of consolidation during ground improvement phase are extremely important. Even though there are large number of analytical methods available to use for the data analysis, not much research is done to identify the tools relevant to the organic soft soils found in Sri Lanka. This research is aimed at investigation of the analytical tools that can be used in the analysis of settlement monitoring data obtained during the implementation of the observational approach for construction of the road embankments over the soft soil deposits in Sri Lanka.

Keywords: Observational Approach, organic soil, Asaoka method, Log time method, hyperbolic method

1. Introduction

Low-lying grounds with soft soil deposits at shallow depths are very often chosen for road traces to minimize issues related to compensation and resettlement. Decision makers in Sri Lanka very often opt this option when new road embankments are constructed in the highly populated western coastal belt. Even though running new road traces through such grounds minimizes certain social issues, geotechnical engineers face a major challenge when constructing high road embankment on such weak compressible grounds to avoid flooding.

Generally there exists a high variability of the ground conditions encountered in soft compressible soil deposits. Due to this an initial design using unfavourable or prismatic ground conditions becomes uneconomical or sometimes not feasible. Therefore, very often most probable or more optimistic ground conditions are considered in the initial design and the risks associated with such assumptions are managed by reviewing the initial design through observational data obtained during the construction stage. This approach is referred as the observational approach.

Apart from the issues related to the stability of the road embankment on very weak ground during the construction stage of the embankment, the assessment of the degree of primary consolidation during the soft ground treatment phase and the estimation of the post construction secondary consolidation settlements during the service stage are major challenges related to the road embankment construction over such soft soil deposits using the observational approach. However, no well defined methodology is available for the implementation of this observational approach in embankment construction over very soft soil deposits. The objective of this research is to investigate the effectiveness of commonly used analytical tools in the implementation of the observational approach for the design and construction of embankments over soft soil deposits in Sri Lanka. In this regard, emphasis is made in this research to investigate the analytical tools used to assess the estimation of the primary and secondary consolidation using observed settlement monitoring data.

2. Background and Approach

Selection of relevant soil parameters is critical for the highly variable soil profile with soft soil deposits. In the observational approach, the most probable material parameters are used for the design, in contrast to the practice of using worst material properties generally used in traditional design approach. Therefore, to prevent failure, the filling rate is controlled according to the rate of deformation of the soft soil deposits under the embankment. For example in the Colombo Katunayake Expressway (CKE) project the settlement per day should be less than 9mm and the lateral displacement should be less than 4mm per day.

The timing of construction processes such as time for removal of surcharge or putting an additional surcharge are carried out based on the estimated degree of consolidation of the soft soil deposit under the embankment using pore pressure measurements and/or settlement monitoring data. However, in most cases pore pressure measurements are not available and the assessment of the degree of consolidation depends mainly on the settlement monitoring data.

A method of predicting the primary consolidation settlement from the observed data has been proposed by Asaoka (1978). It is a graphical approach to estimate final total primary consolidation settlement and settlement rates from settlement data obtained during a certain time period. Ariyaratna and Thilakasiri (2011) based on the data from the vacuum consolidated sections of the soft soil deposits from Southern Expressway Project, showed that the Asaoka method can be used to accurately estimate the total primary consolidation settlement of Sri Lankan peaty soil.

The hyperbolic method (Tan 1971; Chin 1975 & Tan 1995) has also been recognized as an important tool in analyzing settlement monitoring data. Usually this is used to evaluate future settlement, based on measured settlement data. In this method, it is assumed that settlement time curve follows a hyperbolic variation.

Secondary consolidation settlement continues after the end of primary consolidation settlement of peaty soil. Since it causes severe maintenance problems of road embankments constructed over soft soil deposits, the secondary consolidation settlements should be limited to a predetermined value within a certain time period. In the CKE project the settlement of the road embankment should be less than 154 mm within the defect liability period of two years after construction of the road pavement. Therefore, the analysis of the observed settlement data and reliably predicting the future secondary consolidation settlement is of vital importance. One of those methods of predicting of the secondary consolidation settlement from the observed data is the log - time method.

3. Analysis of Settlement Monitoring Data

3.1 Ensuring short term stability during construction stage

The soft soil deposits are highly compressible and possess very low shear strength. As a result, there is a possibility that the embankments constructed over such soil deposits may undergo rotational slope failure. Therefore, depending on the height of the embankment, the soft ground should be strengthened with crushed stone piles (CSP) or sand compaction piles (SCP) or any other suitable method. Even with such ground improvement methods, embankment construction should be carried out in a step wise manner so that soft soil gains strength during loading steps. The installation of CSP, SCP or prefabricated vertical drains (PVD) may enhance the drainage characteristics of the soft soil deposits expediting the primary consolidation process. Unlike CSP and SCP, installation of PVD will not increase the strength of the soft soil deposit.

In the observational approach, the factor of safety against failure of the embankment slopes should be estimated using the methodology explained in Premalal et al. (2012) using the most probable soft soil properties rather than traditionally used most pessimistic soil properties. Due to the use of most probable soil properties, the probability of failure of the embankment slopes is high. As a result, the process of stability analysis should be enhanced by incorporating observations made during the construction stage. Most often settlement of the embankment top and the lateral displacement at the toe of the embankment are used to ensure slope stability during embankment construction. Premalal et al. (2012) showed that analysis of the observed settlement and displacement using Matsuo chart can be used to provide information on a trend of failure of embankment slope.

3.2 Prediction of Primary and secondary Consolidation settlement from Settlement Monitoring Data

As the pore pressure measurement using piezometers is expensive and sometimes not reliable, more often settlement monitoring data are used to estimate the degree of consolidation (DoC) of the soft soil deposit during the treatment stage. There is large number of methods to estimate the degree of consolidation from settlement monitoring data. However, Asaoka method (1978) and Hyperbolic method (Tan 1971; Chin 1975 & Tan 1995) are very commonly used in the field.

3.2.1 Asaoka Method (1978)

In this method the measured time-settlement curve is plotted to an arithmetic scale. In this method, the time settlement graph after reaching the final embankment height is divided into equal time intervals and settlement at each time step, s_i is estimated. The total primary consolidation settlement, s_c is given where the straight line (l) fitted through the points plotted as (ρ_{i-1},ρ_i) intersects the 45° line ($s_{i-1} = s_i$), as shown in Figure 1. From the slope of the graph β_1 the coefficient of consolidation, Cv, can also be estimated. Determination of the degree of consolidation of the soft soil layer and prediction of the time required to achieve 95% degree of consolidation is done using the estimated total primary consolidation settlement, s_c and the settlement observed at present.

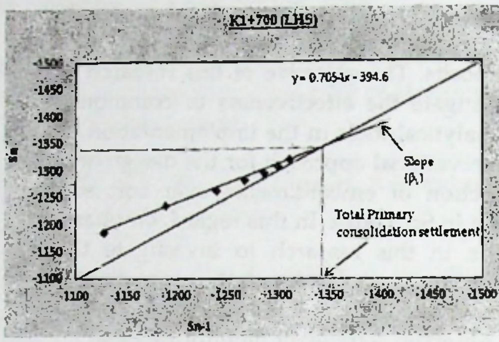

Figure 1: Typical use of the Asaoka method to estimate the total primary consolidation settlement

3.2.2 Hyperbolic Method

The relationship between settlement (δ) and time (t) are assumed to follow a hyperbolic curve by a linear equation given in Eq[1].

$$\frac{t}{s} = B + At \quad ..... (1)$$

Therefore, gradient of this plot can be identified as constant A, as shown in Figure 3. When time tends to infinity inverse of the slope of the graph at linear segment will give the ultimate settlement.

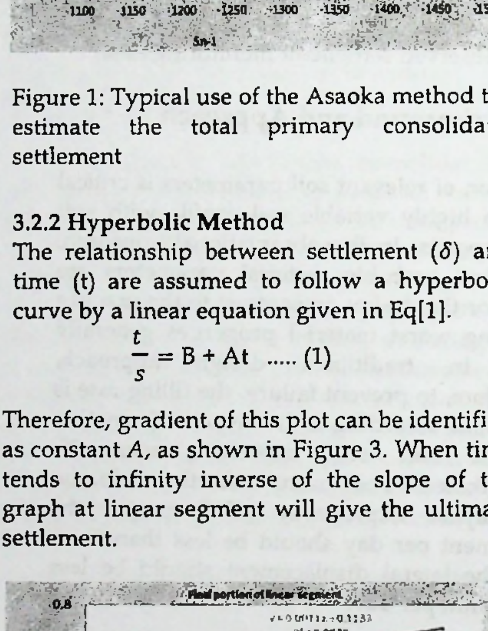

Figure 2: Transformed hyperbolic plot at chainage K5+675 (final segment)

$$\text{Ultimate settlement} = \frac{1}{gradient} \quad ..... (2)$$

For the sample data set from the CKE project chainage at K5+675 shown in Figure 2, the slope is 0.0008 for CL(centreline) and hence, the estimated final CL consolidation settlement is 1250 mm from Eq[2].

It is generally observed that different primary consolidation settlements are obtained when settlement monitoring data segments at different times are considered in the hyperbolic method. For example, as shown in figure 3 the initial segment is used for the calculation of ultimate settlement and the estimated primary consolidation settlement is greater than the value previously found for final linear segment as shown in Figure 3. Tan (1994) proposed reasonable prediction can be made through a correction factor of 0.824 for the inverse of the initial gradient after placing the full embankment load.

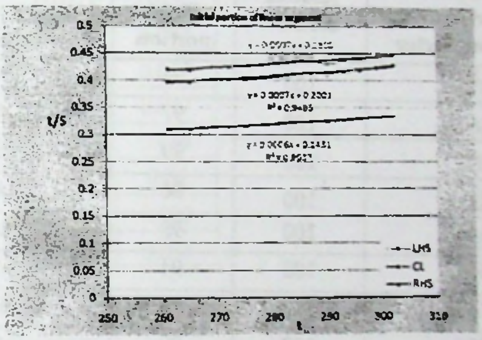

Figure 3: Transformed hyperbolic plot at chainage K5+675 (initial segment)

3.3.3 The Log-time Method

Secondary consolidation settlement (S_s) is given by Eq[3] ,Where t, H, C_α, e_0, and t_p are time, the thickness of the soft soil layer, coefficient of secondary compression, initial void ratio and the time taken for the end of primary consolidation settlement respectively.

$$S_s = \frac{HC_\alpha}{1+e_0} \log\left[\frac{t}{t_p}\right] \quad ..... (3)$$

The assumptions in log time method are the variation of the secondary consolidation settlement (S_s) follows a linear variation with the log of the elapsed time and the secondary consolidation starts after the end of primary consolidation settlement. The observed settlement monitoring data after reaching about 95% degree of consolidation (DoC) is matched by varying the modified compression index C_α' in Eq[4], as shown in Figure 4.

$$C_\alpha' = C_\alpha/(1 + e_0) \quad .....(4)$$

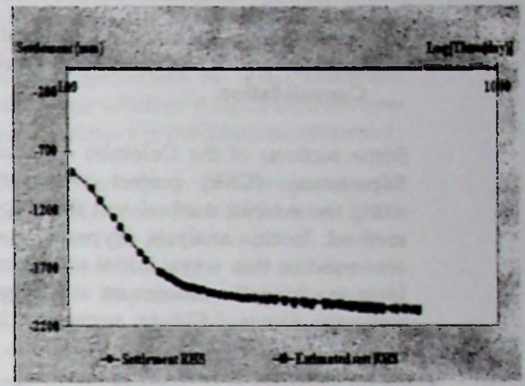

Figure 4: Use of the Log time method to estimate C_α'

After obtaining C_α' values by matching the observed settlement monitoring data after reaching the primary consolidation, the graph is extended as shown in Figure 4, to predict long term secondary consolidation settlement during the service life of the embankment.

Based on laboratory testing and back analysis, Hsi et al. (2005) showed that the modified coefficient of secondary consolidation (C_α') for the soft soils in the Colombo - Katunayake Expressway (CKE) project generally lies between 0.01 to 0.04 as shown in Figure 5.

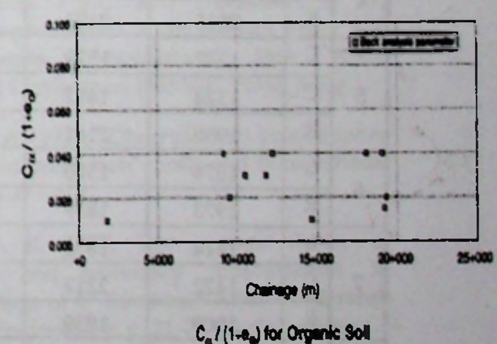

Figure 5: C_α' values from laboratory testing and back analysis after Hsi et al. (2005)

The results of laboratory testing given by Mesri et al. (1997), based on their testing of Middleton peat, indicates the modified coefficient of secondary consolidation (C_α') in a similar range.

4. Results

4.1 Predicted Primary Consolidation Settlements and the Degree of Consolidation

Some sections of the Colombo – Katunayake Expressway (CKE) project were analysed using the Asaoka method and the Hyperbolic method. In this analysis, Hyperbolic method was used in two ways; initial settlement data after reaching the maximum surcharge level with the factor 0.824 as suggested by Tan (1994) and the final segment of the settlement monitoring data. The results are given in Table 1.

The average degree of consolidation is calculated as the ratio between the present settlement and the final consolidation settlement obtained from the Asaoka or the Hyperbolic methods, expressed as a percentage.

Table 1: Comparison of predicted settlements of Asaoka vs. hyperbolic methods

Section		Predicted consolidation settlement			D.O.C.(%)		
		Asaoka method	Hyperbolic method		Asaoka method	Hyperbolic method	
			Final portion	Initial portion with modifying factor		Final portion	Initial portion with modifying factor
1	L	748	925	973	100	94	90
	C	1279	1428	1564	100	97	89
	R	920	1028	1033	100	99	99
2	L	1133	1330	1433	100	96	89
	R	1234	1363	1346	100	98	100
3	L	1339	1570	1665	100	94	89
	C	2039	2217	2146	100	98	100
	R	1730	1839	1995	100	99	91
4	L	1486	1662	1655	100	98	98
	R	2045	2193	2168	100	98	99
5	L	1247	1529	1448	100	92	98
	C	1324	1492	1570	100	96	91
	R	1950	2141	1995	100	96	100
6	L	1076	1570	1665	100	94	89
	R	1973	1839	1995	100	99	91
7	L	1414	1880	2197	100	77	66
	C	1422	2217	2264	99	63	62
	R	1009	1839	1803	100	56	57
8	L	769	935	1199	100	84	66
	C	1138	1209	1306	91	86	79
	R	803	1052	1105	100	79	76
9	L	1269	1369	1376	100	92	92
	R	1156	1174	1383	99	98	83
10	L	1075	1668	1485	100	73	82
	C	1342	1850	1746	100	82	87
	R	706	877	792	100	89	98

4.2 Predicted Secondary Consolidation Settlements

Some sections of the Colombo - Katunayake Expressway (CKE) project were analysed using the Log-time method and the obtained modified compression index C_α' are given in Table 2.

Table 1: C_α' values obtained from the log time method

Section	($C_\alpha' = C\alpha/(1 + e_0)$)	
	LHS	LHS
1	0.044	0.037
2	0.052	0.04
3	0.037	0.023
4	0.042	0.03
5	0.047	0.033
6	0.044	0.037
7	0.044	0.037
8	0.037	0.037
9	0.031	0.034
10	0.034	0.04
11	0.031	0.028
12	0.031	0.035

5. Conclusion

The degree of consolidation (DoC) estimated considering the settlement data immediately after reaching the full embankment load and the same estimated considering the settlement monitoring data closer to the end of primary consolidation agree reasonably well except for very few sections,. This finding will enhance the effective use of the Hyperbolic method, as the DoC can be estimated using the early settlement monitoring data rather than waiting until close to end of primary consolidation settlement.

According to Table 1, it is seen that the degree of consolidation predicted from the Asaoka method is generally more than the same estimated using the hyperbolic method. When one considers the sections with lower degree of consolidation (DoC) estimated from the Hyperbolic method, Asaoka method predicts 100% degree of consolidation. Further, at most of these sections the measured settlements within about three months after reaching the final primary consolidation settlement estimated from the Asaoka method are in the range of about 100 to 200 mm. This indicates that the settlement may include some primary consolidation settlement as well. Therefore, one could argue whether Asaoka method over predicts the primary consolidation settlement.

The above observations are contrary to the findings of Ariyaratna and Thilakasiri (2011), who based on the data from the vacuum consolidated sections of the soft soil deposits from Southern Expressway Project, showed that the Asaoka method can be used to accurately estimate the total primary consolidation settlement of Sri Lankan peaty soil. The probable reason for the contradiction may be the different ground improvement methods considered in this research and by Ariyaratna and Thilakasiri (2011).

Comparing C_α' values reported by Hsi et al. (2005) given in Figure 5 and the findings of this research given in Table 2 indicates good agreement. The estimated modified coefficient of secondary consolidation (C_α') values from back analysis are also in good agreement with the same reported by Mesri et al. (1997) based on their laboratory testing of Middleton peat. However, further research may be required to draw firm conclusions.

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