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Estimating Geotechnical Parameters in Highly Heterogeneous Material Including Peat Deposits using Trial Embankment Data.

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ABSTRACT

When designing high embankments over compressible material it is important to have a sound understanding of the characteristics of the materials in question. When dealing with soils that are highly heterogeneous and consist of many layers of different compressibility it becomes difficult to reliably estimate soil parameters from conventional sampling and laboratory testing. In particular, assessing the magnitudes of primary, secondary and immediate settlement can be difficult as the various layers within the soil consolidate at different rates. This can be further complicated by the presence of peat materials which tend to undergo significant amounts of settlement. An instrumented trial embankment was built over a significant thickness of soft material comprising amorphous peats, organic silts, silts and clays. Soil parameters were back-calculated from monitoring of the trial embankment and these were subsequently used to model the embankment's behaviour using the software package *Settle3d*. The results of the modelling were then calibrated to create a set of parameters which match the settlement data from the trial embankment.

Keywords: Trial Embankment, Settlement, Consolidation, Peat, Settle3d, Compressibility

1 INTRODUCTION

When evaluating geotechnical parameters for the purpose of design, geotechnical engineers typically rely upon laboratory testing data or inferred properties based on site investigations. In larger projects where more accurate soil parameters can represent large costs savings, full scale testing in the form of trial embankments can be an economical method of determining soil parameters and reducing project risk. Primary and secondary consolidation settlements are often difficult to accurately predict and on large highway projects involving soft soils they are a significant risk to both the programme and budget. Indeed, a great proportion of the geotechnical design effort is focused on mitigating and monitoring the effects of settlement. Trial embankments provide a continuous set of data that fully captures all of the various influences on the settlement that cannot be picked up in small scale oedometer testing. However, surface settlement readings from trial embankments do not differentiate between the settlement characteristics of the various discrete soil layers in the same way that a series of oedometer tests can. The primary focus of this paper is to evaluate soil parameters from trial embankment data and the use of Settle3D to model and calibrate these parameters.

2 TRIAL EMBANKMENT

2.1 Description of the Trial Embankment

The trial embankment is 3.3m high and is made out of a compacted sand fill material with a unit weight of around 18kN/m^3. The trial embankment was constructed over a period of 34 days, the exact methodology of construction is unknown to the author and it has been assumed that the trial embankment has been constructed at a steady rate. The top of the embankment measured 18m by 18m with 3H:1V batter slopes.

2.2 Ground profile

The subsurface conditions at the trial embankment were assessed using data from boreholes (BH) and cone penetration tests (CPT) undertaken at the location of the trial embankment. The ground investigation indicated that the trial embankment is directly underlain by a thin stiff crust around 0.5m thick and soft compressible layer around 6.0m thick. Below the soft compressible layer are medium dense sands; the borehole was terminated in this layer at 9m bgl due to the presence of high artesian pressures. For the purpose of this paper the sand layer is assumed to extend indefinitely. The artesian pressures appear to be confined to the sands as the soft compressible layer acts as an aquiclude. The CPT data indicated that the ground water level was at a depth of 0.9m bgl (below ground level). The CPT data can be found in Figure 1.

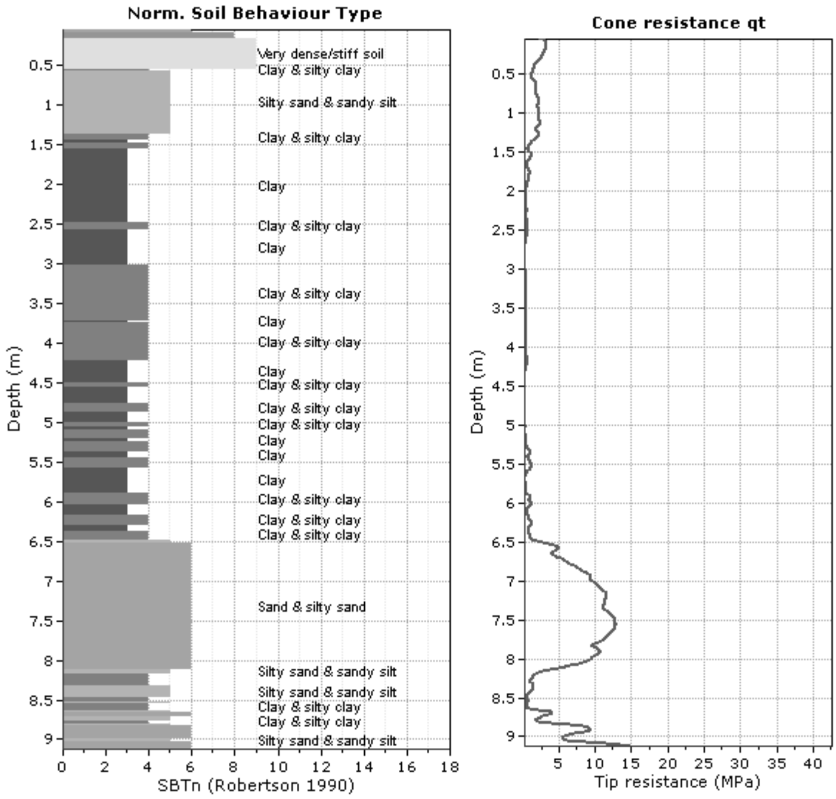

Figure 1. CPT data at the location of the Trial Embankment

The borehole adjacent to the CPT indicates that the upper 6.5m is highly variable and consists of a mix of silt, organic silt, sand, amorphous peat, wood organics, and clay. Much of the compressible layer is understood to be overconsolidated based on correlations with CPT data, this is likely due to the soil being dessicated due to a fluctuating water table. The soil is also assumed to be in double drainage conditions as the embankment above and medium dense sands below the compressible layer are reasonably permeable. A summary of the parameters used in back calculation of compressibility parameters can be found in Table 1 below. These values have been obtained based on a combination of laboratory testing, site obervations and typical values for the material types.

Table 1. Summary of soil parameters from lab testing and empirical correlations

Soil Parameters	**Soft Layer (0 - 6.5m, 8.2 – 8.75)**	**Medium Dense Sands (6.5 – 8.2, 8.75+)**	**Embankment Fill**
G_s (specific Gravity)[a]	2.665	-	-
Liquid Limit (%)[a]	56	-	-
Bulk unit weight (kN/m^3)[b]	15	18	18
E Young's Modulus (MPa)[b]	-	25	-
e_o (void ratio)[a]	1.8	-	-
Over Consolidation Ratio (OCR)[c]	1.5	-	-

[a] Laboratory Testing; [b] Typical soil parameters as per Look (2007); [c] Correlation with CPT data as per Robertson (2012)

2.3 Settlement Monitoring and Results

Profilometers were used to measure the amount of settlement during the trial embankment construction period. The Settlement during construction was measured using two profilometers. After construction was completed a series of survey pins were installed on the top of the fill. These pins were then surveyed continuously for a period of around 580 days at irregular intervals. The results indicate that approximately 100 mm of settlement occurred prior to the completion of the trial embankment. After the completion of the embankment a further 160 mm of settlement occurred.

Three piezometers were installed prior to construction in the borehole undertaken at the trial embankment location at depths outlined in Figure 2. The piezometer readings indicate an increase in pore water pressure of around 47 to 26 kPa immediately after the completion of construction. This is smaller than the estimated total pressure increase due the embankment of 60kPa. The difference in pore water pressure is likely due to the presence of highly permeable layers within the material which quickly dissipate excess pore water pressure during loading. The piezometers indicate that 90% consolidation occurs around 550 days after the start of construction or 520 days after the end of construction.

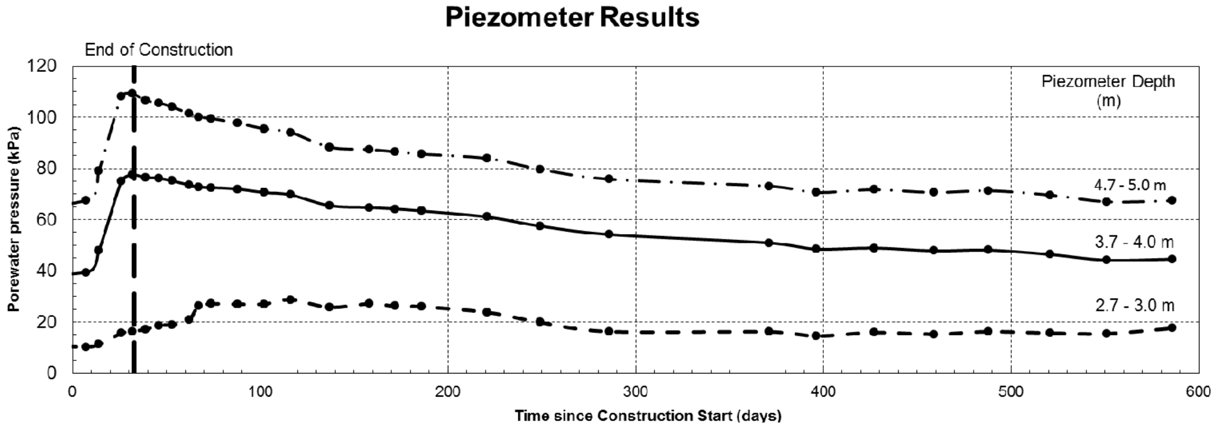

Figure 2. Trial embankment piezometer data

A slowdown in the dissipation of excess pore-water pressure occurred around day 400 and lasted for a period of 150 days. At this time the trial embankment also appears to have risen by around 10mm. This may have been caused by a rise in the water table resulting in increased pore-water pressure and some swelling of the soils as they become saturated. The influence of the rise of the water table on the dissipation of pore-water pressure could potentially have slowed the rate of primary settlement, delaying the time to 90% consolidation.

2.4 Back Calculation of Soil Parameters

To back calculate the compressibility parameters from the trial embankment it is necessary to make some assumptions around what sections of the curve are immediate, primary or secondary. For this exercise the author has assumed that all of the settlement prior to the end of construction is immediate while all of the settlement afterwards is primary settlement. The duration of the trial embankment monitoring data means there is data on the magnitude of secondary compression. The soil parameters were back calculated based on settlement magnitudes from the trial embankment data and the theoretical relationships defined in the equations in Table 2 below. The values used for G_s, w_l, and e_o were as per Table 1. The $\sigma`_{vo}$ was calculated based on the ground conditions prior to the construction of the embankment while the $\sigma`_{pc}$ was determined based on the OCR.

Table 2. Summary of settlement equations used in back analysis

Settlement Type	Equation	Equation Number	Settlement (mm)[d]
Immediate Settlement	$S_i = 1/E_s*H*\Delta\sigma$	1[a]	100
Primary Settlement (Swell Index)	$C_s = 0.0463 * w_l/100 * G_s$	2[b]	–
Primary Settlement (Compression Index)	$S_p = (C_s * H)/(1 + e_o)*\log(\sigma`_{pc}/ \sigma`_{vo}) + (C_c * H)/(1 + e_o) * \log((\sigma`_{vo} + \Delta\sigma) / \sigma`_{pc})$	3[a]	160
Secondary Settlement	Ss = Cα /(1 + eo) * H * log(t2 / t1)	4[a]	–
Consolidation Time	t = (d2* Tv) / Cv	5[c]	–

[a] Terzaghi, Peck and Mesri (1996); [b] Nagarag and Murthy (1985); [c] Terzaghi (1943); [d] Settlement magnitude as measured from the trial embankment

Where:

H is the thickness of compressible material
$\Delta\sigma$ is the change of stress at the centre of the compressible layer
C_s is the swell index
C_c is the compression index
e_o is the initial void ratio
$\sigma`_{pc}$ is the pre-consolidation pressure
$\sigma`_{vo}$ is the initial overburden stress
w_l is the liquid limit
G_s is the specific gravity of the material
S_s is secondary settlement
t_1 and t_2 are the times at the start and end of the interest period
E_s is the constrained modulus
T_v is a non-dimensional time factor
C_v is the coefficient of consolidation
d is the drainage distance
C_α is the secondary compression index

The trial embankment was never unloaded and the data cannot be used to back calculate the swelling index, hence Equation 2 was used.

The trial embankment data available does not cover a period of purely secondary settlement and therefore the author has opted to use the constant relationship between C_α and C_c based on material type. The compressible layer is largely made up of organic silt and as such as per Terzaghi et al (1996) a C_c/ C_α ratio of 0.05 has been adopted. A summary of the back calculated soil compressibility parameters determined can be found in Table 3 below:

Table 3. Summary of back calculated soil compressibility properties

Soil Compressibility Parameter	Soft Layer (0 - 6.5mbgl)	Medium Dense Sands
E_s Constrained Modulus (MPa)	3.45	25
C_v Coefficient of Consolidation (m^2/year)	6	-
C_c Compression Index	0.35	-
C_s Swelling Index	0.07	-
C_α Coefficient of Secondary Consolidation	0.0175	-

3 SETTLE3D MODELLING OF THE TRIAL EMBANKMENT

3.1 Settle3D Inputs

The compressibility parameters and the trial embankment dimensions were then input into RocScience's Settle3d software to model the trial embankment and validate the back calculated settlement parameters. The soil parameters used were as per Table 1 and Table 3 of this report with the compressible layer assumed to have double drainage conditions. The Mesri method of secondary consolidation was chosen and a value of 0.05 was adopted for the C_c/C_α ratio.

3.2 Initial Settle 3D Results and Discussion

The Settle3d results have been summarised in the graph in Figure 3. The graph shows that using the back-calculated parameters the settlement predicted prior to day 200 is overestimated when compared to the actual data, and subsequent to day 200 it is underestimated. This is likely due to the way in which in soil parameters were estimated from the trial embankment. The author has assumed that primary settlement begins at the end of construction and everything prior to that is immediate settlement. In reality, primary and immediate settlement will occur simultaneously during construction. Settle3D is an advanced settlement modelling software and can accurately model the primary settlement during construction.

The largest discrepancy between the Settle3D model and the trial embankment results is the time taken to 90% consolidation. The piezometer data indicate that the trial embankment reached 90% consolidation after 520 days while the Settle3D model indicates that the average degree of consolidation reaches 90% after about 350 days. The author has been thus far unable to exactly determine what is causing this difference in consolidation times. It is possible that this is due to using one dimensional theory to back calculate the C_v value from the trial embankment and then inputting that value into a three dimensional software analysis package.

3.3 Calibration of Settlement Parameters

It is now necessary to calibrate the soil parameters in Settle3d to separate the immediate and primary settlement during construction. The first step when calibrating the model was to establish a relationship between C_c and C_s. Murthy (2002) recommends that a ratio of between C_s and C_c of around 0.2 to 0.1 be used, these have been adopted as the upper and lower bound value. The values of C_v, C_c, C_s and E_s were continuously modified to find a combination of parameters which gives a settlement curve that conforms with the monitoring data from the trial embankment. This process resulted in the development of the soil parameters presented in Table 4.

Table 4. Table summarising calibrated soil parameters

Soil Compressibility Parameters	Soft Layer (0 - 6.5mbgl)	Medium Dense Sands
Constrained Modulus, E_s (MPa)	8.0	25
Coefficient of Consolidation, C_v (m^2/year)	3	–
Compression Index, C_c	0.28	–
Swelling Index, C_s	0.028	–
Coefficient of Secondary Consolidation, C_α	0.014	–

The major difference between the calibrated and back calculated soil parameters is the increase in the constrained modulus, E_s, and the reduction in the C_v value. The increase in the constrained modulus reflects the portion of the assumed immediate settlement which is in reality primary settlement occurring during construction. The settlement curves for both the back calculated parameters and the calibrated parameters can be found in Figure 3 below.

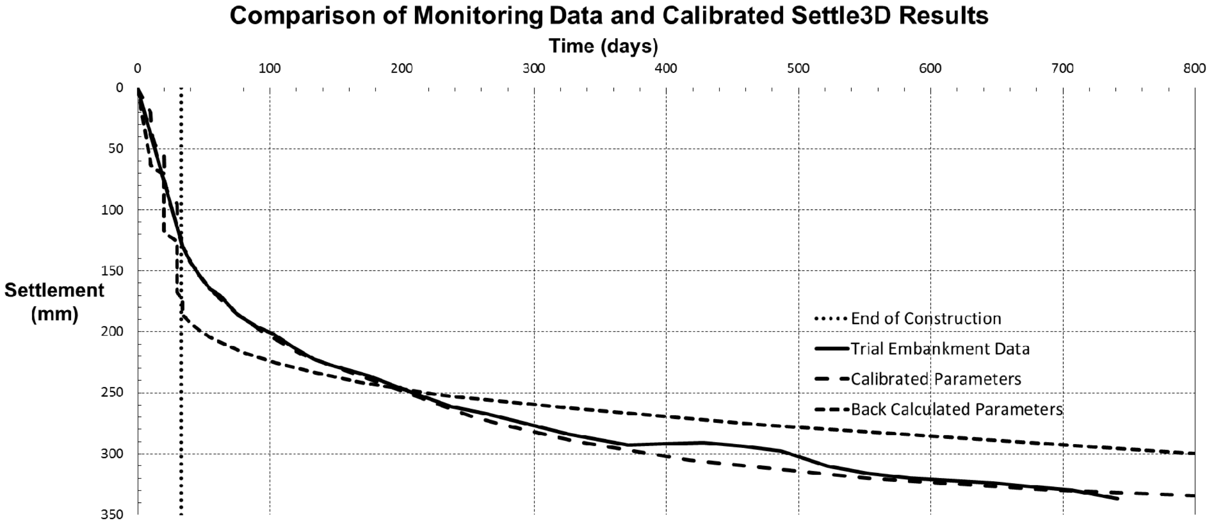

Figure 3. Measured and Settle3D total settlement values for both back calculated and calibrated soil parameters

4 CONCLUSION

Soil parameters have been back calculated from the settlement results of a monitored trial embankment on soft organic material using the standard 1D settlement equations given in Table 2. These soil parameters have been calibrated using Settle3D in an attempt to create a set of parameters that accurately model the trial embankment data.

Differentiating between immediate, primary and secondary settlement in a trial embankment is difficult, especially in soils made up of many heterogeneous layers. Layers will tend to behave differently to each other; sandier layers will tend to undergo relatively large immediate settlements but small primary and secondary settlements whilst very silty or clayey layers will tend to experience small immediate settlements but large primary and secondary settlements. This trial embankment provided settlement data which are an amalgamation of settlement in the different soil layers. This means that while trial embankments provide excellent data on the performance of embankments, they do not provide accurate soil parameters that represent the discrete layers underneath the trial embankment. This can result in back calculated soil parameters from trial embankments giving very different parameters to those obtained from more targeted testing such as oedometers.

An important observation in this trial embankment study was the large amount of settlement prior to the end of construction. Whilst some of this is probably caused by primary settlement mechanisms, a significant portion of it appears to be immediate settlement. This immediate settlement is possibly caused by the compaction of the sandier layers interbedded with the compressible material. Separating the immediate from the primary settlement in the construction period of the curve is almost impossible. To find the portion of immediate and primary settlement during this phase of the curve an iterative process using Settle3D was adopted to determine calibrated soil parameters. The back calculated soil parameters were calibrated using the trial embankment data to come up with a set of soil parameters which the author believes to be a reasonably good approximation of the soils beneath the trial embankment. Due to the difficulties in differentiating between immediate settlement and primary during construction, back calculation of soil parameters would be very difficult in heterogeneous ground conditions without the use of analysis software such as Settle 3D.

Further analysis would be required to determine, through back calculation, the soil parameters for the discrete layers underlying the trial embankment. For the purposes of this study the soft layer was assumed to be a homogenous material. However, borehole investigations indicate that it consist of a heterogonous layer which includes a wide variety of material types from loose sandy silts to amorphous peats. These materials will behave very differently when subjected to embankment loads. A more vigorous analysis would involve separating the soft layer into discrete layers and identifying those which will behave as sand and those that will display more clay-like behaviour. Laboratory testing such as oedometers could be used to define specific soil parameters for these layers and develop a more complex and accurate ground model.

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