Prediction of Primary and Secondary Consolidation of a soft soil in the Sydney Basin

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Summary: This paper presents an approach to predicting the short and long-term consolidation behaviour of a soft alluvial soil in the Sydney Basin. Laboratory testing data, Cone Penetration Testing logs and borehole information were used to characterise the subsoil profile and gain an appreciation of the subsurface variability across the site. Settlement plate, extensometer and piezometer data assisted the tracking of consolidation of the subsurface layers during the application of preload. An assessment of predictive modelling techniques was undertaken and a method developed by Handy adopted to assist in the estimation of time to completion of primary consolidation. This curve-fitting approach to actual data allows the calculation of the practical completion of primary settlement and assists in the prediction of secondary settlement over the life of the proposed development.

INTRODUCTION

The site was a former Industrial Storage Facility located on the bank of the Parramatta River. The proposed development comprises 1 to 2 storey residential development and associated infrastructure. The soft alluvial subsurface across the majority of the site meant that significant improvement of the foundations was required before development could proceed.

The earthworks included 3 main stages to stabilize the soft alluvial sediments across the majority of the site. Firstly, a drainage system was installed to assist in the dissipation of excess pore pressure. Imported regrade fill was then placed and compacted to raise the site above the 1 in 100 year flood level. Finally a 2m layer of surcharge material was placed on top of the regrade fill for a finite period of time to accelerate the rate of settlement. The surcharge layer was left on the regrade layer until an acceptable amount of primary settlement had occurred.

The site investigations, design of the drainage system and preload provisions were carried out by others, prior to URS Australia's engagement to oversee the following:

- installation of drains;
- placement of regrade and surcharge fill; and
- general progress of the preloading.

DRAINAGE SYSTEM

To facilitate drainage of the soft alluvial soils, synthetic wick drains were installed vertically across the site to provide a vertical pathway for the release of porewater, occurring as a result of the consolidation of the soft alluvial soils. These wick drains were installed on a 1.0m, 1.5m or a 2.0m triangular grid depending on the expected settlement and the proposed development of the area. The depth of installation was to the base of the soft soil layer, determined by previous investigations within the area and by resistance of the installation rig. The uppermost 1 to 2 metres of silty sandy material was generally considered to have sufficient permeability to act as a drainage layer for the porewater released from the wick drains. Trench drains with a free draining aggregate were also provided as a secondary drainage path.

IMPORT FILL

The earthworks predominantly involved the placement of imported regrade fill to raise the levels of the foundations to above the 1 in 100 year flood level. This fill consisted of virgin excavated natural sandstone or shale placed in a controlled manner. Additional temporary surcharge fill was placed to facilitate consolidation of the underlying natural soft soils.

INITIAL INVESTIGATIONS AND LABORATORY TESTING

Preliminary geotechnical site investigations were undertaken across the site to characterise the subsurface profile of the proposed development area. Investigations onsite included the following:

- 7 Boreholes drilled to depths ranging between 8.1 and 16.8m;
- 11 groundwater and sampling wells;
- 9 test pits excavated to depths ranging between 0.8 and 2.9m;
- 52 electronic friction cone penetrometer tests (CPT); and
- geophysical survey of the substrata.

Selected samples of the alluvial soils obtained from boreholes were tested in a NATA approved laboratory. The following tests were undertaken:

- Moisture content;
- Atterberg limits,
- Linear shrinkage;
- One dimensional consolidation testing;
- Point load index;
- 4 day soaked CBR;
- Particle size distribution;
- Triaxial testing;

- Chemical tests (chloride, sulphate, nett acid producing potential); and
- Physical tests (pH, conductivity, TDS).

GEOTECHNICAL CONDITIONS

Reference to the 1:100,000 Geological series sheet 9130 (Ed 1 1983) and the initial geotechnical field and laboratory investigation indicates the floodplain area of the site is underlain by silty to peaty quartz sand silt and clay with ferruginous and humic cementation in places. The northern area of the site is underlain by Hawkesbury sandstone, comprising medium to coarse grained quartz sandstone with minor shale and laminate lenses.

The subsurface profile of the site is characterised by two main regions. The profile of the northern region typically consists of topsoil/fill overlying residual clays. Subsurface investigation indicated sandstone bedrock or shale bands lay between 0.8 and 2.7m below ground level. The profile of the southern region of the site typically consists of 1-2m of granular fill overlying alluvial sediments from the Parramatta River. Subsurface investigation indicates the soft alluvial clay deposits range in thickness from 0 to 13m underlain by residual soils and sandstone bedrock. The alluvial deposits are typically interbedded with sandy and silty lenses and bands. Across the site there sediments are highly variable, both vertically and laterally – typical of a fluvial depositional environment.

CONSOLIDATION MONITORING

Prior to installation of the wick drains, extensometers and vibrating wire piezometers were installed at 14 locations across the site to monitor the settlement of the subsurface layers and to observe the groundwater response associated with the settlement. Settlement plates were installed prior to placement of any fill, to allow each plate to stabilize. The plates were used as the primary method for tracking the settlement, as they provide a cost effective coverage of the settlement profile of the site. Where possible, the extensometers were used as a comparison for nearby settlement plates and to observe the settlement behaviour of each layer of material identified. The piezometers were useful as one of the indicators of the completion of primary consolidation (the return of elevated porewater pressures to stable levels indicating the completion of primary consolidation).

PREDICTIVE MODELLING APPROACH

There were two main requirements for predictive modelling of settlement during the project. The principal reason was to assess the time to completion of the primary settlement, to gain an indication of when the preload could be removed to allow the next stage of development to commence. This allowed for timely scheduling of the following works, for example installation of services and infrastructure.

The secondary reason for predicting the time for completion of settlement was to determine if the design surcharge load applied to the regrade fill was likely to give a satisfactory time for completion of primary settlement and to see if alternatives should be considered. Such alternatives include increasing the amount of surcharge to achieve an acceptable amount of settlement within a certain time period or employing other ground improvement techniques such as impact rolling.

PREDICTION OF PRIMARY SETTLEMENT

A number of methods were adopted throughout the course of the project to predict the total amount of settlement and the time to completion of primary settlement. These methods included:

- Hand calculations – hand calculations were undertaken throughout the project using information obtained from CPT logs and boreholes for the profile of the subsurface the laboratory testing. Approximations were and consolidation parameters obtained from made at many locations due to the limited laboratory testing undertaken and the expected variability of the subsurface profile over relatively short distances.
- Asaoka Graphical Settlement Prediction method - The Asaoka method was used during the early stages of the project to obtain an indication of the time to completion of primary settlement. It provides a simplistic approach whereby settlement observations (p_0, p_1,….,p_n) taken at regular time intervals are plotted on a graph in the form (p_j, p_{j-1}). Where the straight line fitted to these points intersects the p_j=p_{j-1} line, is the point of practical completion of the settlement. (Asaoka, 1)
- Handy method – An approach that applies a first order rate equation for predicting the time to completion of the primary settlement. Similar to the Asaoka method of predicting settlement, it does not require a thorough understanding of the mechanisms involved.
- TCON – incremental analysis approach to predicting settlement. TCON is a computer driven program used to model consolidation behaviour. It requires thorough knowledge of the consolidation parameters, the stratigraphy of the subsurface, the loading history of the soil and the applied loading to the subsoil.

Prediction of settlement evolved throughout the project through review of a number of methods and observation of the performance of each method with respect to the onsite filling process and observing the most suitable method.

Initially, the expected amount of settlement was calculated at each of the settlement plate locations. The stratigraphy was interpolated from nearby CPT or borehole logs and an equivalent layer of “significantly compressible” material was identified. This step was undertaken to simplify the analysis due to the limited amount of data on the consolidation parameters of the subsurface material. Consolidation parameters were assigned to the “significantly compressible” layer after assessment of the laboratory testing data and considering the likely variable subsurface profile across the site. A best estimate approach with error bounds was adopted when assigning consolidation parameters. The loading profile at each settlement plate location was determined and the expected settlement calculated.

To calculate the time taken for this settlement to occur, the TCON program was used. TCON analysis enables the operator to enter the subsurface profile, wick drain installation information and an incremental loading profile - typical of the application of compacted regrade and surcharge fill in the field. Problems arose with lack of accuracy due to the number of parameter inputs required and the uncertainty of the values of the parameters. The model required labour intensive frequent calibration to model the actual settlement behaviour onsite and there was no guarantee of its accuracy.

The Asaoka graphical settlement prediction method and a method presented by Handy were identified as predictive modelling techniques where a complete understanding of the mechanisms involved is not required, so long as the mechanisms driving the behaviour are consistent. They both model behaviour whereby an asymptotic approach to an end condition is required. The graphical Asaoka method, as described above, requires settlement to be measured at regular time intervals. The method presented by Handy allows each settlement data point to be used to develop a relationship between the observed settlement and time.

Taking in to account the accuracy of knowledge of the input factors including consolidation parameters, the extended loading profile and the parameters associated with the drainage system, the Handy method was deemed to be the most appropriate method for tracking and prediction of primary settlement. It did not require accurate knowledge of the consolidation parameters, was an appropriate tool for the settlement mechanisms involved and provided a reasonable and appropriate level of accuracy for estimation of the settlement.

HANDY MODEL

The Handy method is based on Terzaghi’s consolidation rate equation based on an analogy between the flow of water out of soil under pressure and the thermodynamics of heat flow (Terzaghi et al, 2).

$$\log\left(e - e_p\right) = -\left(k_t t + C_t\right) \quad \textbf{(1)}$$

where,

e = void ratio,

e_p = final primary consolidation void ratio for a particular applied pressure;

t = consolidation time;

k_t = constant; and

C_t = constant.

“The equation is solved by substituting trial values for e_p until a linear plot is obtained as indicated by the regression coefficient. An equation for void ratio versus time then may be written from the results of the linear regression analysis.” (Handy, 3).

SETTLEMENT MODELLING DIFFICULTIES

The first order rate equation presented by Handy can be used to obtain a good prediction for the completion of primary settlement, however it does not take into account the process of secondary settlement. Secondary settlement is the ongoing consolidation the soil undergoes at constant effective stress, due to the rearrangement of soil particles.

In the field, it is difficult to separate primary settlement from secondary settlement especially when considering thick layers of consolidating clay. Some regions near the drainage surface may have undergone 100% of the primary settlement and be commencing secondary settlement, whereas regions further from the drainage surface may still be undergoing primary settlement (Holtz & Kovacs, 4). While the wick drains installed across the site reduce the effective drainage path for thick soil deposits, the different settlement mechanisms still occur simultaneously.

During the initial stages of primary settlement, the majority of the settlement occurring within the soil layer is primary settlement. Terzaghi’s first order rate equation analogy provides an accurate prediction of the likely time to completion of the primary settlement. As time continues, the soil elements closer to the drainage surface complete the primary settlement stage and enter the secondary settlement stage. The proportion of the observed changes in total settlement that is due to primary settlement gradually reduces. Towards the end of primary settlement, the majority of the change in total settlement may be secondary settlement. As this occurs, the application of a first order rate equation to the observed settlement becomes less valid, as the mechanisms controlling the settlement gradually change.

To account for this change in conditions controlling the settlement of the soil, consideration was given to the following factors when modelling the primary settlement:

- The total amount of settlement expected;
- Expected rate of secondary settlement at the completion of primary settlement;

- The time taken for primary settlement to occur; and
- The thickness of the equivalent layer of compressible material.

When the Handy model presented is used to model the observed settlement, the effect is for a conservative estimate of the time to completion of primary settlement to occur. The greater the secondary settlement component of the total settlement, the more conservative the estimation is likely to be. This was taken into account when assess the time at which surcharge fill could be removed.

It was important to estimate the expected rate of secondary settlement at the completion of primary settlement to ensure that the settlement occurring was indeed secondary settlement. The following section details the process adopted for prediction of secondary settlement.

PREDICTION OF SECONDARY SETTLEMENT

Estimation of the secondary settlement across the site was important during the project to predict the settlement rate at the completion of primary settlement and to gain an indication of the potential settlement of any structures constructed onsite over their service life. The total expected secondary settlement and the potential for differential settlement was estimated to assess the potential impacts on the foundation systems and to develop design recommendations for the site to manage potential ongoing settlements.

Factors influencing the amount of secondary settlement a structure is likely to undergo include the following:

- Time to completion of primary settlement;
- The design time period of the structure (design life);
- Consolidation parameters (primary and secondary);
- Surcharge effort; and
- Layer thickness.

Discussion of how each factor influences secondary settlement is presented below.

TIME TO COMPLETION OF PRIMARY SETTLEMENT

As discussed, the time to completion of primary settlement influences the total amount of secondary settlement observed post surcharge removal as primary and secondary settlement occur simultaneously. The longer the time period for primary settlement to occur, the greater the amount of secondary settlement, prior to surcharge removal.

In a laboratory analysis, the duration of the primary consolidation stage is typically small due to the loading control available. As a result, only a limited amount of secondary settlement can occur during the primary settlement phase. In the field, where compacted fill is placed in relatively thin layers (typically 300mm), the rate loading is limited to how fast the fill is placed, compacted and tested. The staged placement of compacted fill over large areas can extend over months, resulting in a comparatively long time for primary settlement to occur. As the primary settlement phase is over an extended time period, there is equally an extended period of time over which secondary settlement can simultaneously occur.

To assess the magnitude of secondary settlement, the ratio t/t_p is calculated, where t is the total time and t_p is the time for completion of primary settlement. In laboratory analysis of secondary settlement, t/t_p can be typically very large, resulting in secondary settlement after surcharge removal being quite significant. In the field, where t_p is typically longer, secondary settlement after surcharge removal is likely to be less significant. "Typically, for the useful life of the structure, the value of t/t_p rarely exceeds 100 and is often less than 10." (Terzaghi et al, 2)

Assuming a typical design life of 50 years, t/t_p for this project was below 100, with t_p's ranging from 6 months to 18 months. Areas with larger values of t/tp typically had thin equivalent layers of compressible material. For these areas, while secondary settlement may have a greater proportion of the total settlement, the total settlement is still likely to be small.

SECONDARY COMPRESSION INDEX

An appreciation of the behaviour of the secondary compression index, C_α, with respect to time is needed to predict the long-term secondary settlement of a structure. Terzaghi, Peck and Mesri (2) provide a discussion on the potential behaviour of C_α in post surcharge secondary compression, identifying the possibility of the index increasing, remaining constant or decreasing with time. However, C_α/C_c remains approximately constant in both recompression and compression ranges at any time during secondary compression, permitting the secondary settlement behaviour to be predicted.

For geotechnical materials ranging from granular soils to peat, C_α/C_c ranges from 0.01 to 0.07 respectively with inorganic clays and silts typically 0.04 ± 0.01. A compressibility index ratio of 0.05 was adopted for secondary settlement predictions as the subsurface profile typically consisted of a thin layer of peat underlain by a deposit of varying thickness of soft clay. (Terzaghi et al, 2)

A secant, C_α", is identified for practical analysis of secondary settlement (see Figure 1). The prediction methodology is detailed below.

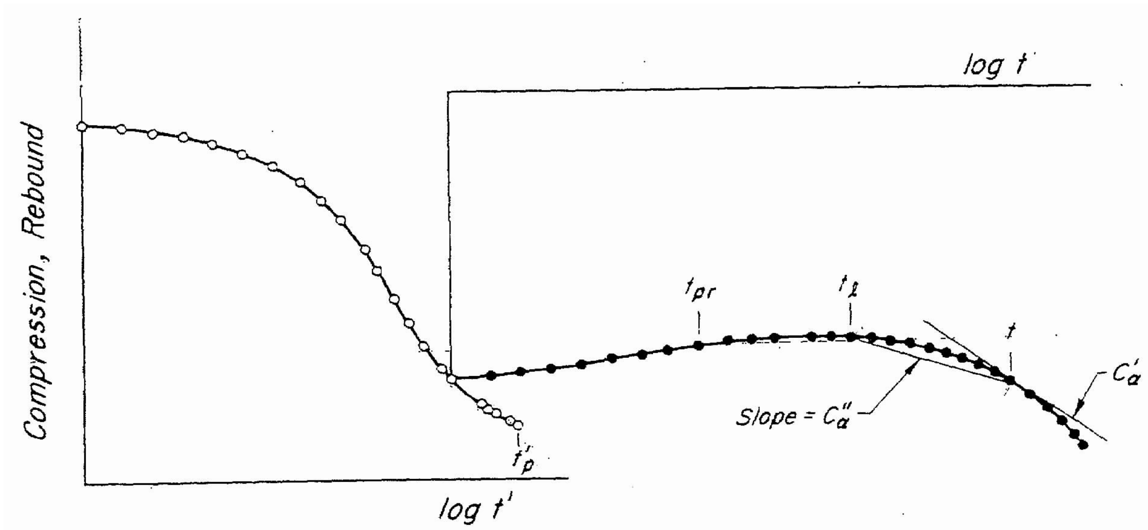


Figure 1: Settlement Behaviour - Surcharge Removal (Terzaghi et al, 2)

SURCHARGE

Surcharging was undertaken to reduce post construction settlement and to accelerate the rate of primary settlement.

The removal of the surcharge leads to rebound of the subsurface, with both primary rebound and secondary rebound occurring. The primary rebound time, t_{pr}, and secondary rebound time, t_l, depend on the rebound characteristics of the soil as well as the permeability and drainage boundary conditions. The value of t_l is determined from the empirical correlation between t_l/t_{pr} and R_s as presented below.

SECONDARY SETTLEMENT PREDICTION PROCEDURE

The following procedure identifies the methodology used to predict the likely secondary settlement at various settlement plate locations across the site.

STEP 1

Initially, the soil profile parameters were defined at a number of locations. The level of the water table, the thickness of the equivalent compressible layer and the unit weights of the existing and imported soil elements were estimated. These parameters were then used to determine the effective stress on the midpoint of the equivalent compressible layer.

STEP 2

The Effective surcharge ratio, R_s', was then calculated.

$$R_s' = \frac{s'_{vertical\_surcharge\_stress}}{s'_{vertical\_post-surcharge\_stress}} - 1 \quad \textbf{(2)}$$

(Terzaghi et al, 2)

STEP 3

The primary rebound time after surcharge removal was then calculated.

$$t_{pr} = \frac{Td^2}{C_{vs}} \quad \textbf{(3)}$$

For areas without wick drains,

C_{vs} was obtained from laboratory oedometer testing;

$$d = 0.5 \times thickness \quad of \quad compressible \quad layer$$

$$T = \frac{(p/4)(U_{av}\%/100)^2}{\left[1-(U_{av}\%/100)^{5.6}\right]^{0.357}} \quad (4) \qquad \text{(Das, 5)}$$

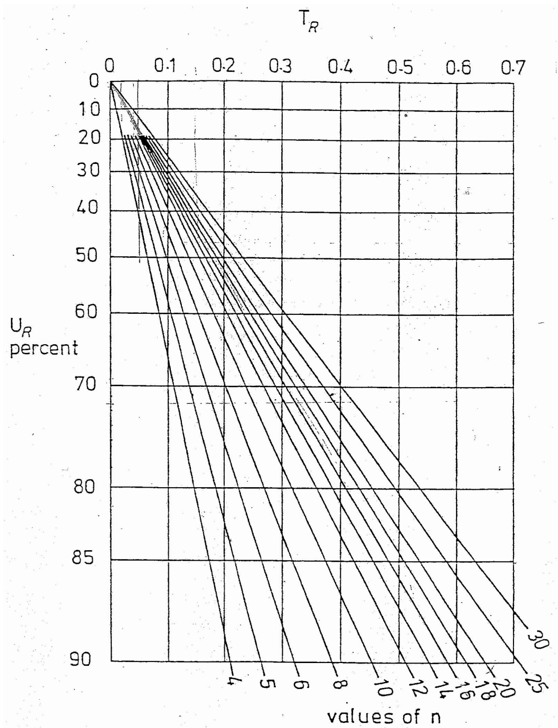
For areas with wick drains,

C_{vs} was obtained from laboratory oedometer testing

$$d = 0.525 \times triangular \quad wick \quad drain \quad spacing$$

T was obtained from Figure 2.

Figure 2: Graph relating T, U and n



(adapted from Richart, 6)

STEP 4

The secondary rebound time after surcharge removal is then calculated from the following empirical equation.

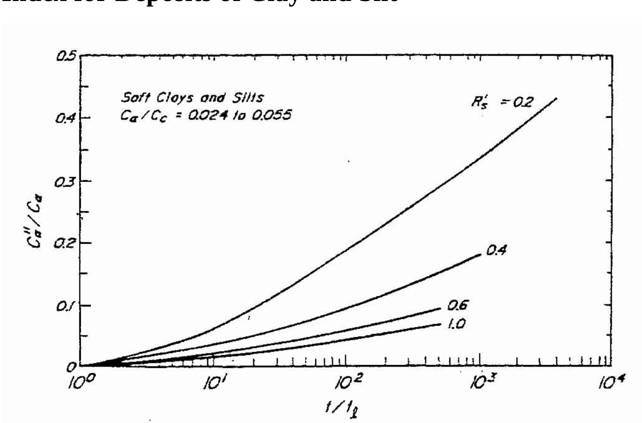
$$\frac{t_l}{t_{pr}} = 100 R_s^{'1.7} \quad \textbf{(5)}$$

(Terzaghi et al, 2)

STEP 5

The secant C_α" was then estimated from Figure 3.

Figure 3: Post Surcharge Secondary Compression Index for Deposits of Clay and Silt



(Terzaghi et al, 2)

STEP 6

The total post surcharge secondary settlement was then calculated using equation 6.

$$S = \frac{C''_a}{C_a} \frac{C_a}{C_c} C_{ec} L_0 \log \frac{t}{t_l} \quad \textbf{(6)}$$

(Terzaghi et al, 2)

CONCLUSIONS

The Handy method presented is considered to be the most appropriate method for predicting the time to completion of primary settlement for field analyses, where there is limited knowledge of the subsurface profile and material characteristics. The approach models future settlement based on real data recorded and does not require accurate knowledge of the subsurface profile, the loading profile or the consolidation parameters of the soft sediment layers. The Handy method should be used in conjunction with calculations based on traditional consolidation theory, to ensure the settlement behaviour observed is relatively consistent with expectations.

It is acknowledged that predictions based on the Handy model become less accurate and more conservative as completion of primary settlement approaches. The gradual increase in secondary settlement as a proportion of the total settlement leads to an overestimation of the total primary settlement. The error associated with the increasing proportion of secondary settlement can be managed, provided the secondary settlement at the completion of primary settlement has been assessed.

Careful consideration should be given to the amount of secondary settlement any developments on site will undergo settlement amounts can be significant. Substantial differential settlements can occur as a result of secondary settlement over the design life of a structure and appropriate foundation design is important to reduce the potential for the occurrence of structural damage. Significant factors influencing the settlement of the structure include the time taken for primary settlement, the design life of the structure, the surcharge effort, the layer thickness of the consolidating material and the consolidation parameters of the subsoil material.

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REFERENCES

1. Asaoka, A., "Observational Procedure of Settlement Prediction", Soils and Foundations, Vol 18, No. 4, December 1978, pp 87-101.

2. Terzaghi, K., Peck, R.B., Mesri, G., (1996) "Settlement during Secondary Consolidation Stage," Soil Mechanics in Engineering Practice, Third Edition, pp108-110.

3. Handy R.L., "First-Order Rate Equations in Geotechnical Engineering", Journal of Geotechnical and Geoenvironmental Engineering, Vol, 128, No. 5, May 1 2002.

4. Holtz, R.D., Kovacs, W.D., (1981)"An Introduction to Geotechnical Engineering", Prentice Hall.

5. Das, B.M., (1987) "Advanced Soil Mechanics", McGrawHill, p. 511.

6. Richart, F. E., (1959), "Review of the Theories for Sand Drains," TRANS. ASCE, Vol.124, 1959.