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Estimation of creep settlement reduction due to surcharging using commercially available software

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ABSTRACT: Surcharging is one of the preferred ground improvement techniques widely used today for construction of road embankments over compressible soils in many infrastructure projects. Surcharge generates pre-consolidation pressures of the soils under the embankment larger than the final effective stress post surcharging. By increasing OCR due to surcharging in the analysis, the calculated creep settlements are expected to be reduced.

While built-in settlement codes developed by researchers or practitioners can include creep reduction due to surcharging, most commercially available software does not have special modules to consider this feature.

This paper discusses a simplified approach to use commercially available software to estimate the creep settlement reduction effect by means of the ratio of creep strain rate in overconsolidation state to normally consolidated state. The software selected are Plaxis2D and Rocscience's Settle3D and comparisons of results obtained from both software are presented.

1 INTRODUCTION

The increasing development and rapid expansion of transport infrastructure projects in recent years has resulted in the need for construction of many projects over soft compressible soils. These projects typically occur on low lying marshy areas or estuarine environments that contain soft organic compressible clay and peat deposits. These soft soil deposits are characterised by low shear strength, low bearing capacity, low permeability and are highly compressible which results in excessive settlement and large differential settlements. Therefore, efficient and robust ground improvement techniques are critical to providing the foundation that many of these transport infrastructure project are constructed upon. The combination of preloading with surcharge and wick drains/Prefabricated Vertical Drains (PVD) is one of the most widely used ground improvement techniques due to its economic viability, effective application, and simple construction technique.

During preloading, when a temporary surcharge load is applied to an embankment in excess of the final construction load, the rate of settlement through primary consolidation can be accelerated and the secondary compression component commences. To reduce the secondary compression using surcharge loading, either the secondary compression index or creep strain rate is required to be improved. After removal of the larger surcharge load, the soil material will swell for a certain duration followed by resumption of secondary compression under a new constant effective stress at a lower rate of creep strain rate, $C_{\alpha\varepsilon}$ than it would without the applied surcharge load.

In this paper, an approach of secondary compression (creep) reduction by preloading with surcharge using commercially available software has been proposed. This simplified approach explores the effect of secondary compression reduction by assessing the ratio of creep strain rate in overconsolidation state to the normally consolidated state using Plaxis2D and Rocscience's Settle3D.

A case study is used to illustrate the method by modelling the construction of a hypothetical road embankment over soft compressible soil deposits.

2 SECONDARY COMPRESSION OR CREEP

2.1 *Theory of secondary compression*

Mesri and Godlewski (1977) introduced the secondary compression index, C_α as a ratio of change in void ratio, e, to a time period (in logarithmic scale) in which secondary compression is calculated (refer Figure 1). C_α is as expressed as:

$$C_\alpha = \frac{-de}{d(\log t)} \tag{1}$$

The secondary compression strain, ε, is calculated using the following equation:

$$\varepsilon = \frac{C_\alpha}{1+e_c}\log(\frac{t}{t_c}) \quad (2)$$

Where e_c and t_c is the void ratio and time at the start of secondary compression, respectively. t_c is theoretically considered at the end of the primary consolidation.

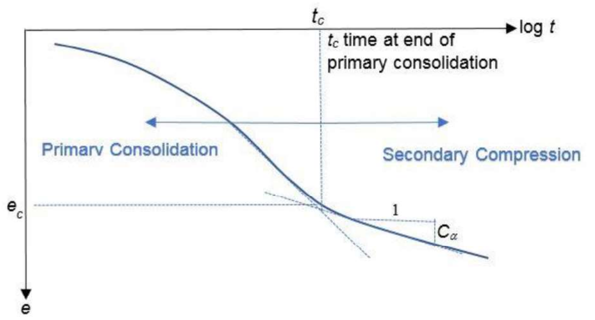

Figure 1. Settlement curve showing secondary compression.

An alternate expression of the secondary compression index called creep strain rate or rate of secondary consolidation, $C_{\alpha e}$ (Wong, 2006a) is often used as below.

$$C_{\alpha e} = \frac{C_a}{1+e_c} \quad (3)$$

Both the secondary compression index and creep strain rate can be obtained directly from oedometer test results for different set of loadings.

2.2 *Initiation of secondary compression*

There is always a question of initiation of the secondary compression. In general, if a compressible soil layer is thin (e.g. a soil sample in an oedometer test), secondary compression will start following the end of primary consolidation. If a compressible soil deposit is thick, secondary compression may start earlier during the primary consolidation stage

There are two hypothesises about the initiation of secondary compression used in practice as discussed by Hsi et al. (2017).

The first hypothesis assumes the secondary compression commencing after the end of the primary consolidation and the effective stresses in the soil is constant.

The second hypothesis assumes the secondary compression commencing within the consolidation process. Creep strains will develop in both primary consolidation and secondary compression stages.

2.3 *Secondary compression reduction with surcharge*

Figure 2 presents a typical strain-time relationship from the primary consolidation stage, surcharge removal and secondary compression stage developed by Ladd in 1971 (Hsi et al., 2017).

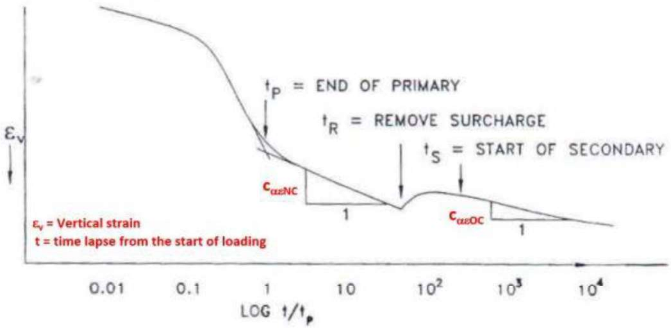

Figure 2. Strain-time relationship with surcharge removal (after Ladd, 1971 in Hsi et al., 2017).

A surcharge will cause a larger effective stress in a soil element below embankment. This stress will be a new pre-consolidation pressure of the soil element. Once the surcharge is removed, the over-consolidation ratio (OCR) of the soil increases and hence the creep strain rate decreases as shown in Figure 2.

Several authors discuss creep improvement ratio after surcharge in different forms (e.g. Mesri et al. 2001, Conroy et al. 2015 and Wong, 2006b). Any formulation on creep reduction can be implemented and chosen for the procedures suggested in this present study.

The present study used the empirical expression suggested by Wong (2006b) as below.

$$\frac{C_{\alpha\varepsilon(OC)}}{C_{\alpha\varepsilon(NC)}} = \frac{(1-m)}{e^{(OCR-1)n}} + m \quad (4)$$

where $C_{\alpha\varepsilon(OC)}$ is the creep strain rate per log time cycle for OC soil at an OCR state, $C_{\alpha\varepsilon(NC)}$ is the creep strain rate per log time cycle for NC soil, m and n are parameter constants. The values of m and n are 0.1 and 6, respectively.

3 NUMERICAL ANALYSIS METHODS

3.1 *Overview of Plaxis2D software*

Two constitutive plasticity models in Plaxis2D – the soft soil model and the soft soil creep model can be used to model time dependent behavior of compressible soils. The first model can only analyse consolidation case. The latter model is specially developed to analyse both consolidation and secondary compression of soft compressible soils.

By differentiating the inverse of eq (2),

$$\frac{1}{\dot{\varepsilon}} = \frac{t-t_c}{C_{\alpha e}} \quad (5)$$

The above expression was proposed by Janbu in 1969 (Plaxis 2017) as shown in Figure 3. Such a curve can be created from oedometer test results with constant load. The boundary between consolidation and secondary compression is defined with the intersection of the curve line and the straight line.

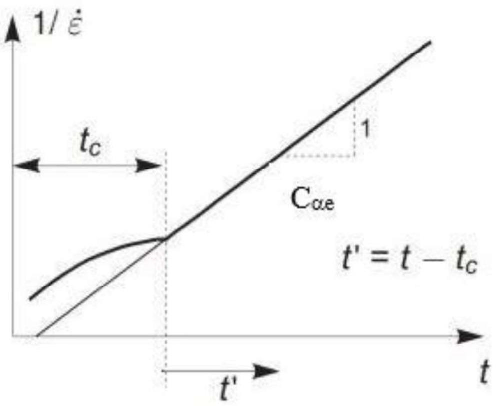

Figure 3. Inverse secondary compression strain versus time.

Based on the above expression, a differential equation for 1D creep model and further extended into a 3D model have been incorporated in the Plaxis model. The basic approach is that there are two components of strain during loading, elastic, ε_c^e, and inelastic strains, ε^p, as shown in Figure 4. All inelastic strains are time dependent. Inelastic strain comprises the inelastic consolidation, ε_c^p, and creep strain, ε_{cr}^p. σ'_o, σ'_p, σ'_{pc}, and σ' are the initial effective pressure, preconsolidation pressure before loading, pre-consolidation pressure at end of consolidation state and final pressure during a relatively long creep period, respectively.

The model also shows that creep strains are functions of the over-consolidation ratio as well as the ratio of compression index ratio, C_{ce} and creep strain rate, $C_{\alpha e}$.

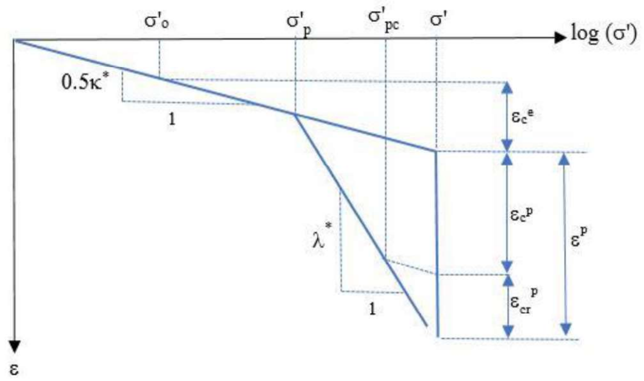

Figure 4. Idealised stress-strain consolidation-creep curve.

The plastic behavior of the plasticity model is governed by the combination of the Mohr-Coulomb failure yield function and the cap yield function which is determined with a parameter M defining the ratio of horizontal to vertical stresses in primary one-dimensional compression, K_0^{nc}. However, the creep formulation does not include failure.

Plaxis used parameters κ^*, λ^* and μ^* which can be correlated to C_{re} (swelling index ratio), C_{ce} and $C_{\alpha e}$ as follows:

$$\kappa^* = \frac{C_{re}}{1.15} \quad , \lambda^* = \frac{C_{ce}}{2.3} \quad , \mu^* = \frac{C_{\alpha e}}{2.3} \qquad (6)$$

Note that the soft soil creep model in Plaxis allows creep strains generated once there is effective stress. In contrast to thin soil samples in consolidation tests in laboratory, most soft soils in nature are quite thick and subject to initial stresses prior to external loading, applying the soft soil creep model from beginning of the analysis will allow creep to be generated without additional loading. Consequently, allowing creep simultaneously with consolidation may overpredict the final settlement.

3.2 *Overview of Settle3D software*

The settlement analysis in Settle3D is based on one-dimensional consolidation analysis including creep at user defined time intervals. Multi-stage layers of embankments are allowed, and visualisation can be presented in 3-dimensions. Loading is distributed in 3-dimensional space with options up to five stress computation methods. The Boussinesq loading distribution method was chosen in this study.

In Settle3D, there are two methods for creep analysis. The first method is the standard method as discussed in Section 2.2 and the second method is the Mesri method (Rocscience 2009) which depends on the ratio of secondary compression index to compression index that allows to vary especially during surcharging.

In line with the Plaxis analysis, the standard method is applied here. Settle3D allows the initiation of secondary compression by setting up a percentage of consolidation. This option can be defined in advanced options menu in the Project Settings Dialog.

Furthermore, the reduction of rate of secondary compression can be assigned in soil properties menu. Figure 5 shows an example of how to reduce the rate of secondary compression in Settle3D.

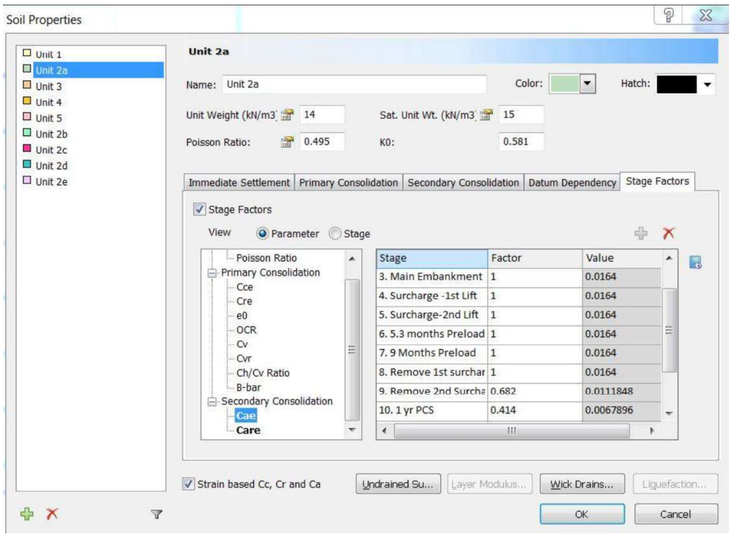

Figure 5. Soil properties menu in Settle3D.

3.3 *Numerical procedure for creep analysis*

The proposed procedure allows the creep commencing at a certain degree of consolidation of compressible soils under the main embankment plus surcharge.

For each soft soil layer, two soil models need to be defined in Plaxis 2D– soft soil model and soft soil creep model. The soft soil model is applied in the earlier stage of analysis and then the soil properties are changed to the soft soil creep model when creep needs to be included in later construction stages of the analysis.

For Settle 3D, both consolidation and creep properties can be defined at each soft soil layer as there is an option for users to activate secondary consolidation (creep) as discussed in Section 3.2.

Figure 6 shows the procedures proposed for creep analysis in this paper. The flowchart shows that a complete set of consolidation analysis needs to be performed first to determine a time when creep will start. A target of consolidation (as in Step 3) or another criterion such as a target time can be assigned. Note that these criteria should be considered carefully depending on available geotechnical information, types of soil testing techniques and experience.

For steps 4 and 5 when only consolidation is carried out, the soft soil model for Plaxis2D analysis is assigned.

From step 6, the soft soil creep properties need to be assigned to replace the soft soil model for each sub soil layer. Such creep properties then need to be adjusted using equation (4) for each surcharge removal in Steps 8 and 9.

4 NUMERICAL EXAMPLE

4.1 *Geotechnical properties*

A 3 m high embankment constructed over 10 m thick soft soils is chosen for this study. This example is a hypothetical model which the main embankment geometry is based on the Ballina trial embankment (BTE) in NSW (Chan et al., 2018), but other features like soil layers, soil properties, wick drain spacing are purposely modified to achieve the main objective of the present study to show how commercial software (i.e. Plaxis2D and Settle3D) can be used to estimate creep settlement reduction due to surcharging.

For this example, 2 m surcharge and wick drains (PVD) at 2 m spacing are required to meet residual settlement criteria of 100 mm in 40 years after construction (After surcharge removal). It was also assumed that the Hold Point on surcharging is released at degree of consolidation of 85%.

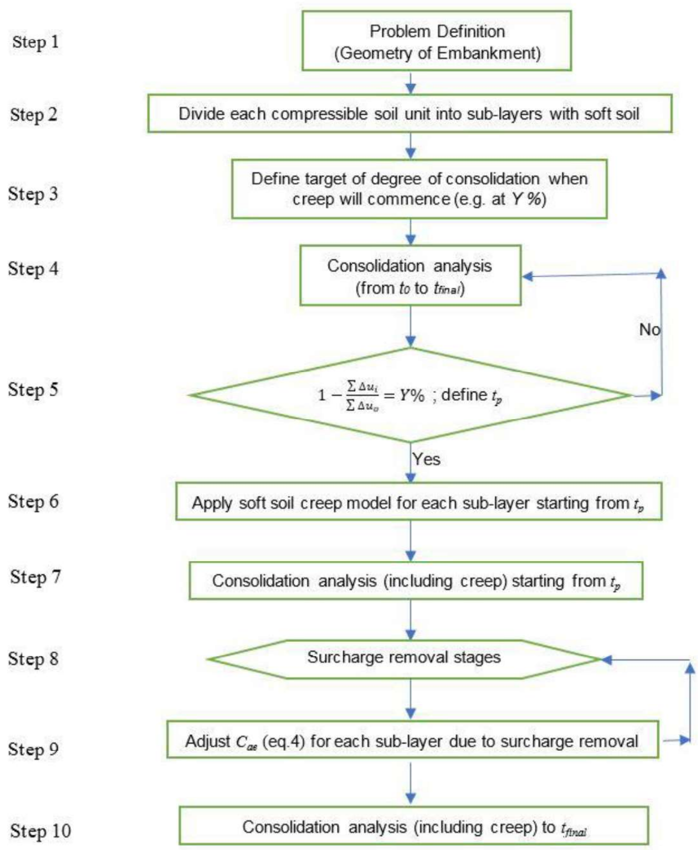

Figure 6. Proposed procedure for creep reduction analysis.

Figure 7 shows the geotechnical section for the embankment with a uniform 10 m thick layer of estuarine silty clay subdivided into five sub-layers. The boundary conditions modelled in Plaxis 2D is extended to 60 m to left and right.

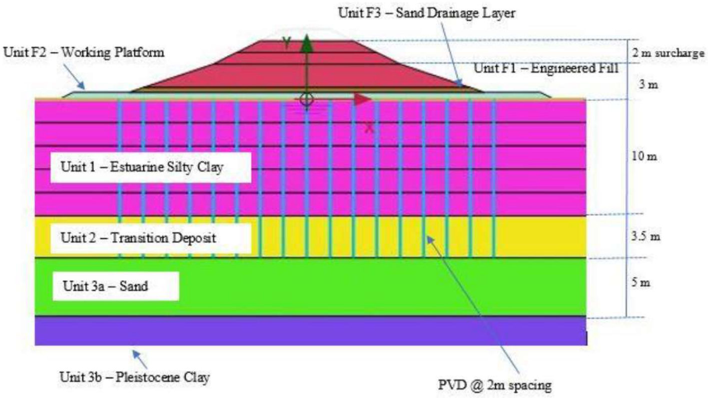

Figure 7. Geometry of the model embankment.

4.2 *Geotechnical properties*

Only Unit 1 has compressibility properties while other materials were modelled using Mohr-Coulomb properties. The geotechnical properties for Unit 1 and other geotechnical units are provided in Table 1 and Table 2, respectively.

Table 1. Consolidation and creep properties.

Description	γ	κ^*	λ^*	μ^*	c'	ϕ'	*OCR*
Silty Clay	15	0.0181	0.1708	0.0071	2	30	1.25

γ = Unit weight (kN/m^3)
c' = Effective cohesion (kPa)
ϕ' = Effective friction angle (degree)
OCR = initial Overconsolidation Ratio

The swelling index ratio (C_{re}), compression index ratio (C_{ce}) and creep strain rate ($C_{\alpha e}$) adopted for Settle3D are correlated using equation 6.

Table 2. Geotechnical Properties for non-compressible soils.

Unit	Description	γ	E	ν	c'	ϕ'
2	Transition deposit	18	12	0.3	2	30
3a	Sand	19	40	0.3	0	41
3b	Pleistocene Clay	19	30	0.3	5	32
F1	Engineered backfill	20	35	0.3	-	-
F2	Working platform	21	35	0.3	-	-
F3	Sand drainage layer	19	30	0.3	-	-

γ = Unit weight (kN/m^3)
E = Elastic modulus (MPa)
ν = Poisson's Ratio

4.3 *Construction sequences*

The construction sequences adopted in the analysis are summarised in Table 3 below.

Table 3. Construction sequences adopted in the analysis.

Stage	Description	Duration (days)
1	Construct working platform	3
2	Construct 3 m high embankment	16
3	Construct 1 m 1st lift surcharge	5
4	Construct 1 m 2nd lift surcharge	5
5	Consolidation analysis (to 85% degree of consolidation – 5.3 months after surcharge)	158
6	Consolidation up to 9 months after surcharge	113
7	1st surcharge removal	3
8	2nd surcharge removal	3
9	Continue analysis to 40 years after removal	14400

4.4 *Numerical results*

The output of the final settlements of the Plaxis2D and Settle3D analyses are presented in Figures 8 and 9, respectively.

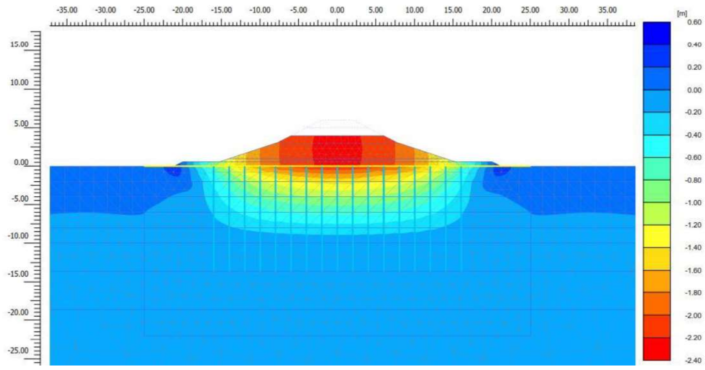

Figure 8. Plaxis2D settlement output.

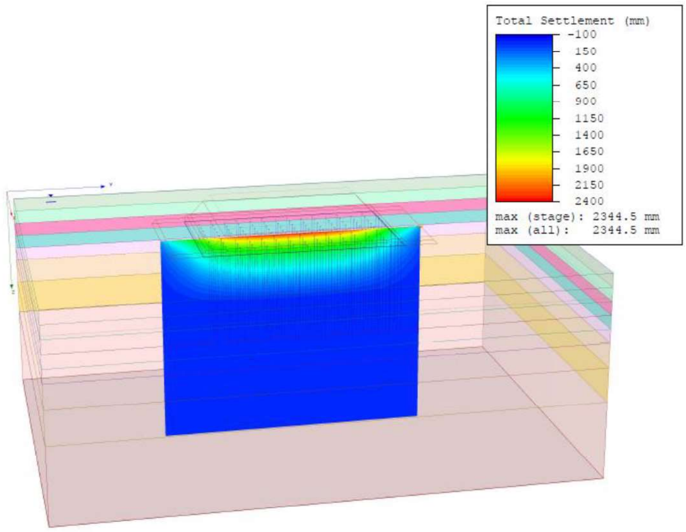

Figure 9. Settle3D settlement output.

The final settlements calculated at the end of analysis obtained from Plaxis2D and Settle3D analyses are almost similar, 2,333 mm and 2,346 mm, respectively. However, the curves of settlement versus time show slight differences. Settle3D appears to have instantaneous settlement during the short loading time of embankment and surcharges. Once passing this stage, the gradients of settlements of the two analyses are almost similar as shown in Figure 10.

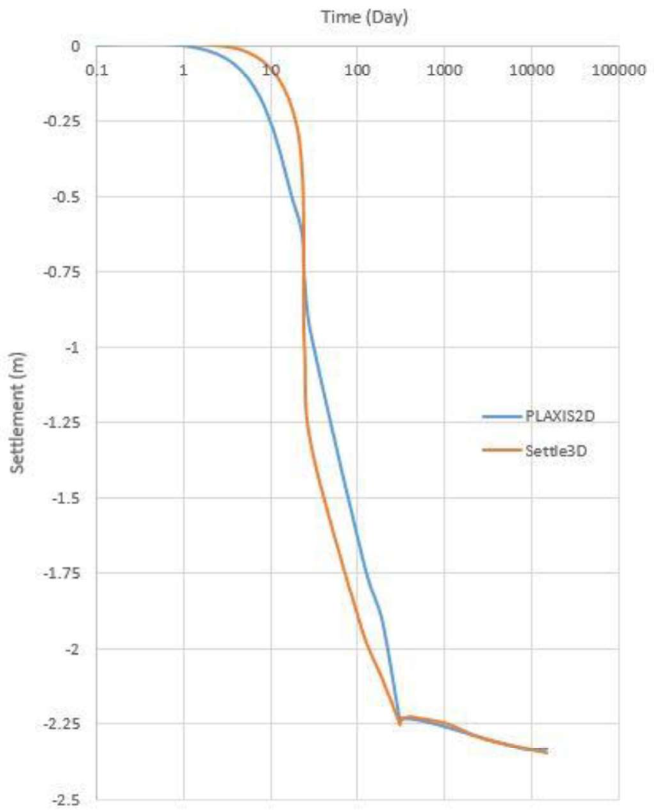

Figure 10. Settlement Curve with time.

The new OCR value calculated from the ratio of the final effective stresses post surcharging to those prior to surcharging are better defined as Yield Stress Ratio (Kelly et al., 2017). This terminology is better used to distinguish with the initial OCR assumed in the model (i.e. OCR in Table 1).

The magnitude of creep after surcharge removal shows agreement between the two analyses although the percentage reductions of the creep strain rates of the two analyses are quite different as shown in Tables 4 and 5.

In general, Settle3D has larger reduction of creep strain rate, however, these differences have only little impact to the final settlement values.

5 CONCLUSIONS

This paper summarises a simplified approach using commercially software (Plaxis2D and Settle3D) to estimate the creep settlement reduction effect. The proposed procedure for creep reduction analysis discussed in Section 3.3 can be applied in both Plaxis2D and Settle3D analyses.

Comparisons between the Plaxis2D and Settle3D analyses show good agreement in the final settlement prediction. There are differences in the reduction of creep strain rate, but this has only little impact to the final settlement values.

As the soft soil creep model in Plaxis allows creep strains generated once there is effective stress, the use of this model needs precaution with regards to practical application. It is possible to combine both soft soil model and soft soil creep model to prevent overestimated settlement.

Table 4. Reduction of creep strain rate following 1st surcharge removal.

	Plaxis2D		*Settle3D*	
Sub-layer	*YSR*	*% creep rate*	*YSR*	*% creep rate*
1	1.014	92.9	1.073	68.2
2	1.017	91.3	1.096	60.6
3	1.020	90.0	1.103	58.4
4	1.022	89.1	1.090	62.5
5	1.031	84.7	1.075	67.3

Table 5. Reduction of creep strain rate following 2nd surcharge removal.

	Plaxis2D		*Settle3D*	
Sub-layer	*YSR*	*% creep rate*	*YSR*	*% creep rate*
1	1.071	68.7	1.175	41.4
2	1.051	76.3	1.206	36.2
3	1.045	78.9	1.231	32.5
4	1.044	79.1	1.203	36.6
5	1.062	71.9	1.170	42.5

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