PRELOAD DESIGN, PART 2 – AN ANALYTICAL METHOD BASED ON BJERRUM'S TIME LINE PRINCIPLE AND COMPARISON WITH OTHER DESIGN METHODS

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ABSTRACT

Following a review of time-dependent settlement behaviour and preload design methods presented in Part 1 of this paper (Wong, 2006a), Part 2 of this paper presents the development of an analytical approach for preload design based on Bjerrum's (1967; 1972) time line model, or principle of "artificial aging". This analytical approach can be readily coded using an Excel spreadsheet for assessing the required preload thickness to limit post-construction settlement to a specified value.

A worked example is presented and compared with other methods (Mesri, 1991; Poulos, 2004; PLAXIS Version 8, 2002) to illustrate the importance of geological and stress history on post-preload settlement behaviour.

The dependency of creep on stress level and stress history is used in the analytical approach introduced in this paper, and the results of the worked example clearly show the reasons for the possibility of significant post-preload creep settlement if the amount and/or the degree of consolidation during surcharging were insufficient.

The purpose of this paper is not to suggest any preference for a particular preload design method with respect to either correctness or accuracy in predicting post-construction settlement performance following preloading. Rather, through the worked example, it highlights the dependency of the results on certain assumptions used in the models, and perhaps also highlights the importance of being able to follow the stress path and applying fundamental principles to explain the predictions and their limitations.

1 INTRODUCTION

In Part 1 of this paper (Wong, 2006a), the stress level-dependency and stress-history dependency of creep was introduced, and the following equation was suggested by the author for assessing the creep strain ratio of an over-consolidated soil:

$$\frac{C_{\alpha\varepsilon(oc)}}{C_{\alpha\varepsilon(nc)}} = \frac{(1-m)}{e^{(OCR-1)n}} + m \tag{1}$$

where:

OCR = over-consolidation ratio (whether due to past higher stress, creep or "aging process", or other factors.

$C_{\alpha\varepsilon(oc)}$ = creep strain rate per log time cycle for an over-consolidated soil at a particular OCR.

$C_{\alpha\varepsilon(nc)}$ = creep strain rate per log time cycle for a normally consolidated soil (i.e. OCR =1) and is stress level dependent (see Figure 2 of Wong, 2006a).

m and n = constants depending on soil type, values of m = 0.1 and n = 6 are considered by Wong (2006a) to be reasonable values for organic soils in the absence of site specific data (see Figure 4 of Wong, 2006a). It is possible that higher "n" values may be possible based on back analysed data from Alonso *et al.* (2000).

Based on a modified form of Bjerrum's time line approach, Wong (2005) presented an analytical method for preload design that could be incorporated into a simple spreadsheet to assess the preload thickness required to achieve a given design embankment height and post-construction settlement limit. This approach incorporates the weight of the embankment fill, including the settled fill below the ground level and buoyancy effects of the settled fill.

The main difference in the method described by Wong (2005) and Bjerrum's time line approach (Bjerrum (1967; 1972) is that there is no need to assume that the lines representing the creep characteristics of a soil are parallel in the e –log (p) plot. While the varying creep rates shown by the "splaying out of the creep lines" with increasing effective stress in Figure 1 appear to be a very bold deviation from the parallel creep lines shown in Bjerrum's conceptual model, they represent a conceptual model that takes into account the dependency of creep strain with stress level. In the analytical approach that is described below, it does not really matter whether the creep lines are drawn parallel or splayed, provided the appropriate creep strain value is selected, depending on stress level and stress history. In other words, the key is to have a reasonable assessment of the appropriate creep strain value for long-term post surcharge settlement assessment purposes, which is also true for the preload design method described by Mesri (1991).

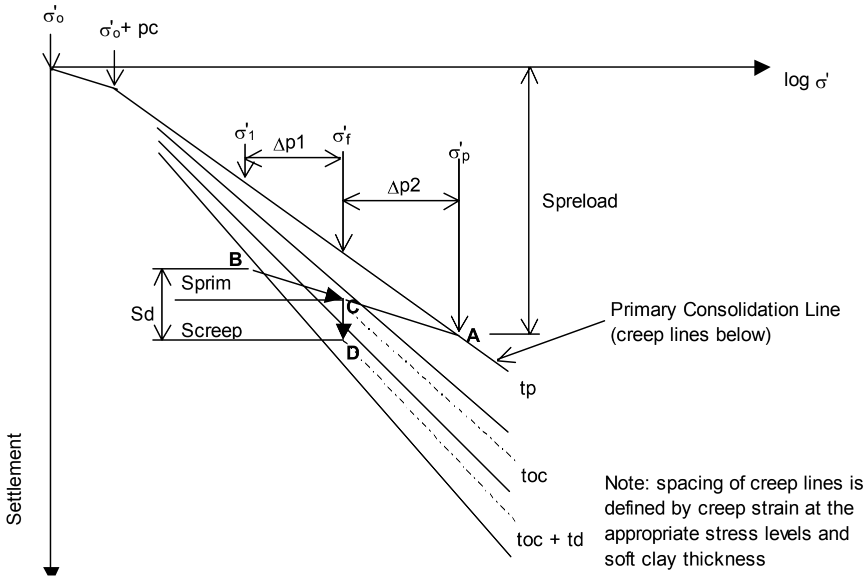

Figure 1: Development of Analytical Approach Using a Modified Form of Bjerrum's Model.

The points in Figure 1 are defined as follows:

Point A = Effective stress σ'_p reached after preloading with degree of consolidation U_p

Point B = Effective stress σ'_1 after removal of preload and rebound has occurred

Point C = Effective stress σ'_f after final design stress applied and primary consolidation S_{prim} occurred

Point D = Final settlement including creep after design life of t_d

Sd = Design post-construction settlement limit after ground improvement by preloading

Sprim = Primary consolidation component of S_d (reloading after preloading)

Screep = Creep component of S_d (over-consolidation creep after preloading)

Δp_1 = Design stress increase after preloading from project loads

Δp_2 = Effective stress increase above final stress, σ'_f, from preload at degree of consolidation, U_p

tp = Reference time for primary consolidation to occur (or primary rebound after surcharge)

toc = Equivalent "artificially aged" time after preloading

td = Design life after application of final stress increase associated with project.

In this approach, a key parameter (besides the other soil compressibility values) is the choice of the creep strain rate, $C_{\alpha\varepsilon(oc)}$, at the appropriate stress level and OCR corresponding to the final stress following removal of the surcharge and after application of the design load to account for the lower creep strain due to the artificial aging process in a similar way as the secant C_α" value used by Mesri (1991), reproduced as Figure 5 in Wong (2006a). It should be pointed out here that $C_{\alpha\varepsilon(oc)}$ used in this paper is equivalent to Mesri's C_α"/(1+e_o)

Another key parameter which will have an influence on the analysis result is the reference time, t_p , which is used to assess creep at a constant effective stress, and the equivalent "artificially aged" time, "toc" following removal of the surcharge and application of the final loading. This reference time is referred to as the instantaneous compression line in Bjerrum's original time line diagram (reproduced as Figure 1 in Wong (2006a), and is shown as a 24 hour line in keeping with the time for each load increment in the standard oedometer test. In preload assessment in the field, however, the onset of significant creep generally occurs much later than 24 hours even though the author believes that creep occurs simultaneously with primary consolidation as discussed in Wong (2006a). This is usually the case even if wick drains are used to accelerate primary consolidation. From the author's experience, a t_p value of 1 year appears to be reasonable for most practical projects when used with the analytical method described in this paper.

2 ANALYTICAL SOLUTION

Using the modified time line concept, a set of equations have been developed for the general case of a soft ground that requires filling to form a final construction platform followed by the application of development loading as shown in Figure 2.

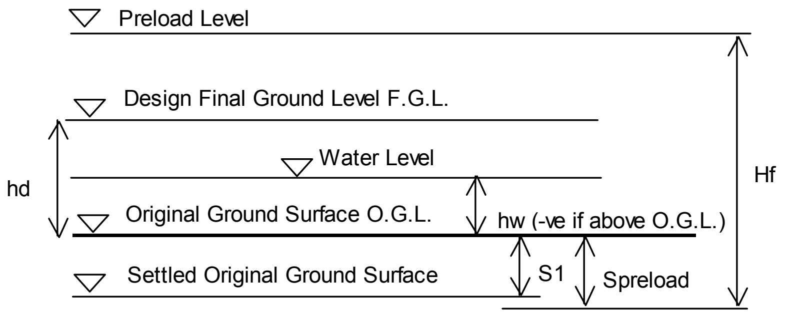

Figure 2: Problem Definition for Development of Preload Design.

The formulation of the preload design calculations takes account of the following:

- Settlement of the preload fill or working platform
- Buoyancy of the fill that settles beneath the ground water level
- Percentage consolidation under the preload (stress increase is assumed to be proportional to percentage consolidation)
- Dependency of creep strain rate on stress level and stress history.

An iterative approach is adopted, requiring an initial estimate of the settlement under the preload. The initial estimate is then checked against the computed value until a match is found that provides the corresponding preload fill thickness. The steps in the analytical approach (modified from Wong (2005) by iterating against an initial trial preload effective stress (rather than settlement during preloading to make spreadsheet computation easier) are as follows:

Step 1

Divide the soft soil profile into sub-layers, and for a given time available for preloading, calculate the degree of consolidation, Up, achievable under the preload for each sub-layer using the traditional one-dimensional consolidation theory and the diagram shown in Figure 3.

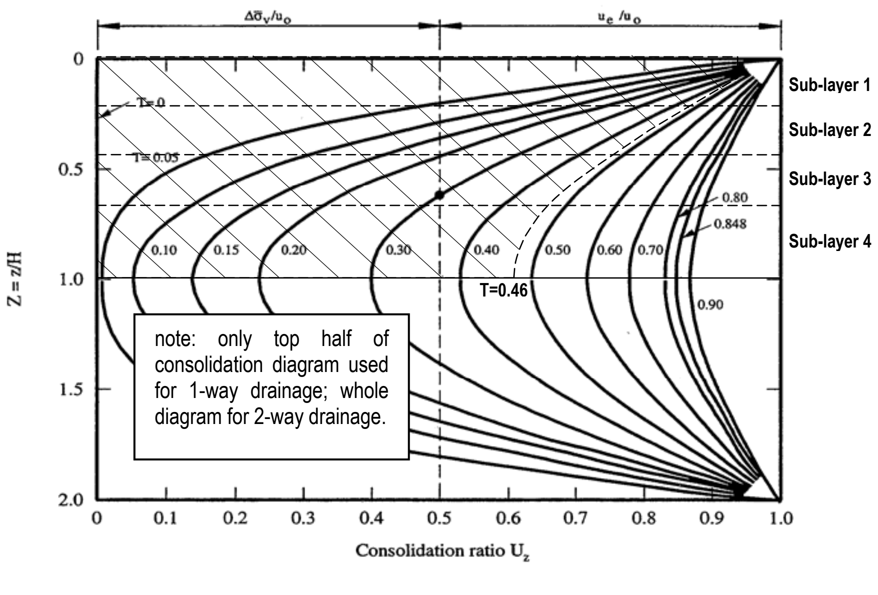

Figure 3: Degree of Consolidation as a Function of Depth and Time Factor (Lambe and Whitman, 1969).

Step 2

Trial an initial effective stress (including buoyancy effects) applied by the preload including the embankment and surcharge filling (note: a trial and error approach is not necessary if Excel's "SOLVER" function is used (see Step 11). The effective stress at the end of preloading, σ'_p is defined for each layer as:

$$\sigma'_p = U_p \times p'_{trial} \times I_z \tag{2}$$

where: U_p degree of consolidation from Step 1
p'_{trial} = trial initial stress applied at original ground level
I_z = depth influence factor to take into account of 2D or 3D loading conditions

Step 3

The settlement, S_A, for each sub-layer is calculated by applying the classical one-dimensional settlement equation:

$$S_A = h_o\left[\frac{C_r}{1+e_o}\log\left(\frac{\sigma_o'+p'_c}{\sigma_o'}\right)+\frac{C_c}{1+e_o}\log\left(\frac{\sigma'_p}{\sigma_o'+p'_c}\right)\right] \tag{3}$$

and the total settlement during preloading is integrated over the profile to obtain $S_{preload}$.

Step 4

Knowing the total settlement, $S_{preload}$ during preloading, the equivalent preload thickness, H_f , corresponding to the trial effective stress, is calculated based on the input target degree of consolidation and buoyancy effect due to the settled fill using the unit weight of the fill and water level information as defined in Figure 2.

Step 5

The final effective stress following removal of the surcharge to the design embankment height and the rebound, S_r , is calculated for each sub-layer so that the net settlement at point B (Figure 1) is $S_B = S_A - S_r$.

The amount of surcharge fill to be removed at this step is:

$$H_r = H_f - S_{preload} - h_d \tag{4}$$

But it should be pointed out that the stress decrease due to surcharge removal in each sub-layer for calculation of rebound needs is not $H_r \times \gamma_f$ unless the degree of consolidation during preloading has reached 100% for that sub-layer. The stress change from point A to point B may be calculated as follows:

$$(\Delta p_1 + \Delta p_2) = \sigma'_p - (h_d \times \gamma_f + S_{preload} \times \gamma'_f) \times I_z \tag{5}$$

where: $S_{preload}$ and I_z are as defined in the previous steps, and
γ_f and γ'_f = bulk unit weight and buoyant weight of the embankment fill respectively.

If $(h_d \times \gamma_f + S_{preload} \times \gamma'_f) \times I_z < \sigma'_p$, the rebound from point A to point B may then be calculated as follows:

$$S_r = h_o\left[\frac{C_r}{1+e_o}\log\left(\frac{\sigma'_p-(\Delta p_1+\Delta p_2)}{\sigma'_p}\right)\right] \tag{6}$$

It can be seen from Equations 5 and 6 that if $(h_d \times \gamma_f + S_{preload} \times \gamma'_f) \times I_z > \sigma'_p$, $(\Delta p_1 + \Delta p_2)$ will be negative and further primary consolidation will occur even after unloading. In this situation of insufficient preloading, Equation 6 should not be used, and S_r should be set to zero for that sub-layer and the future primary consolidation, S_{prime} , may be calculated as follows:

$$\text{For } (h_d \times \gamma_f + S_{preload} \times \gamma'_f) \times I_z > \sigma'_p \rightarrow S_{prim} = h_o\left[\frac{C_c}{1+e_o}\log\left(\frac{\sigma'_p-(\Delta p_1+\Delta p_2)}{\sigma'_p}\right)\right] \tag{7}$$

In the latter situation, not only is S_{prim} positive (i.e. further settlement rather than rebound), the magnitude is 5 to 10 times (i.e. ratio of C_c/C_r) higher than S_r compared to the case of sufficient preloading.

Step 6

The final effective stress following application of the design load and the corresponding primary consolidation component, S_{prim} is calculated. As discussed in Step 5, depending on the degree of preloading achieved at the time of removal of the surcharge, S_{prim} may undergo reloading (sufficient preloading) or virgin loading (insufficient preloading) or a combination of both.

For each sub-layer, the settlement at point C (Figure 1), S_C, is now calculated as $S_B + S_{prim}$.

Step 7

The settlement at σ_f' on the primary consolidation line directly above point C (Figure 1), if preloading had not been carried out, is calculated as S_{CO} as follows:

$$S_{co} = h_o\left[\frac{C_r}{1+e_o}\log\left(\frac{\sigma_o'+p'_c}{\sigma_o'}\right)+\frac{C_c}{1+e_o}\log\left(\frac{\sigma'_f}{\sigma_o'+p'_c}\right)\right] \quad \textbf{(8)}$$

Step 8

The OCR value after Step 6 is calculated and the new $C_{\alpha\varepsilon(oc)}$ value is assessed using Equation 1. The procedure for calculating the final OCR is relatively simple (i.e. σ'_p/σ'_f). However, incremental OCR values are required to enable the "artificially aged" time, "toc", to be calculated because the creep strain rate is not constant with time. That is, the spacing of the creep lines is reducing with each log time cycle because the process of creep causes an increase in the preconsolidation pressure as discussed in Wong (2006a). By dividing the difference in effective stress between σ'_p and σ'_f in to a number of increments (say "N" equal increments; N=5 is generally sufficient), it is possible to compute the creep strain rate and "toc" as follows:

Average OCR at increment "i" → $$OCR_{(i)} = \frac{\sigma'_f+(i-0.5)\left(\frac{\sigma'_p-\sigma'_f}{N}\right)}{\sigma'_f} \quad \textbf{(9)}$$

$C_{\alpha\varepsilon(oc)(i)}$ at this increment → calculate creep strain rate according to Equation 1 using $OCR_{(i)}$

S_c at this increment → $$S_{c(i)} = S_{co}+h_o\left(\frac{C_c-C_r}{1+e_o}\right)\log\left(\frac{\sigma'_f+i\left(\frac{\sigma'_p-\sigma'_f}{N}\right)}{\sigma'_f}\right) \quad \textbf{(10)}$$

"Aged" time at this increment → $$toc_{(i)} = toc_{(i-1)}10^{\left[\frac{Sc(i)-Sc(i-1)}{C_{\alpha\varepsilon(oc)(i)}(h_o-S_{c(i-1)})}\right]} \quad \textbf{(11)}$$

Equations [9] to [11] are repeated from i = 1 to N to obtain the final "toc". In the above procedure, if $\sigma'_p < \sigma'_f$, then $C_{\alpha\varepsilon(oc)}$ should be set to $C_{\alpha\varepsilon(nc)}$ and "toc" should be set to "t_p" (i.e. normally consolidated condition).

Step 9

The final OCR and $C_{\alpha\varepsilon(oc)}$ are then calculated using OCR = σ'_p/σ'_f for each sub-layer, and the long-term creep settlement, S_{creep} can now be estimated as follows:

$$S_{creep} = C_{\alpha\varepsilon(oc)}(h_o-S_C)\log\left(\frac{toc+t_d}{toc}\right) \quad \textbf{(12)}$$

Step 10

Integrating over the soft soil profile, the total post-construction settlement is estimated from Steps 6 and 9 as (S_{prim} + S_{creep}).

Step 11

Steps 2 to 10 are then iterated, or Excel's SOLVER function is used until the following conditions are satisfied:

- $(S_{prim} + S_{creep}) \leq S_d$, and **(13)**
- $(H_f - S_{preload}) \geq h_d$ **(14)**

It should be stressed that the above analytical procedure is not a time-dependent analysis and does not include the effect of simultaneous consolidation and creep. Compared to more complex time-dependent simultaneous consolidation and creep models, however, this simplified procedure does allow a ready visualisation of the stress path that the various sub-layers in the soil profile undergo in either Bjerrum's original time line model shown in Figure 1 of Wong (2006a), or the modified model shown in Figure 1 of this paper.

3 COMPARISON OF ANALYTICAL METHOD WITH OTHER METHODS

The analytical method described in Section 2 above is used in the following example which is also compared with analysis results carried out using (a) the approach of Mesri (1991), (b) a finite difference program CAOS-1D developed by Poulos (2004), and (c) simultaneous consolidation and creep model of the commercially available program PLAXIS (Version 8, 2002).

3.1 EXAMPLE PROBLEM

A proposed road embankment having a design height of 3 m constructed over 9 m of soft soil is used in this example:

Soft clay profile = 9 m thick
Groundwater level at surface
Bulk unit weight = 15 kN/m^3
0 m to 2 m OCR = 10
2 m to 4 m OCR = 4
4 m to 6 m OCR = 2
6 m to 9 m OCR = 1.2
$C_c/(1+e_o) = 0.3$
$C_r/C_c = 0.1$
$C_{\alpha\varepsilon(nc)} = 0.015$ at an effective stress level of approximately 100 kPa (if normally consolidated)
$c_v = 15$ m^2/yr (one way drainage with impermeable base)
Design embankment height, $h_d = 3$ m
Bulk unit weight of embankment fill and surcharge = 20 kN/m^3
Design load = 8 kPa (reduced live load factor of 0.4 × design traffic loading of 20 kPa)
Available surcharge time = 2.5 yrs
Road to open approximately 0.5 yr following removal of surcharge.

For this example, we will consider that the task is to find the required fill thickness, H_f , (including embankment fill, settlement, and surcharge) to limit post-construction settlement to 0.1 m in 20 years after construction.

3.2 ANALYTICAL APPROACH USING THE TIME LINE CONCEPT AS DESCRIBED IN SECTION 2

Within an available preload time of 2.5 yrs, the dimensionless time factor is calculated to be $T_v = c_v.t/H^2 = 0.46$, and an average degree of consolidation of 73% of the entire profile may be inferred from 1D consolidation theory. However, if we subdivide the profile into four sub-layers having thicknesses of 2 m, 2 m, 2 m, and 3 m, the degree of consolidation may be read from Figure 3 as approximately 93%, 80%, 70%, and 62% in each of the four sub-layers respectively.

The need to place more fill than the design height to compensate for settlement and surcharge causes additional loading and settlement, making it difficult to achieve high OCR for the soft soil without placing large amounts of preload fill. Staged construction is normally required to maintain adequate stability although not discussed in this paper.

Using a simple spreadsheet developed based on the analytical procedure described in Section 2, and adopting a reference time, t_p , of 1 year, the amount of preload fill required is assessed to be 6.4 m, with an estimated settlement of 1.04 m during preloading, leaving an excess fill of 2.36 m (i.e. 6.4 m-3 m-1.04 m) to be removed. However, this surcharge is found to be only partially effective due to the limited preload time and percentage consolidation achieved as indicated above.

The stress paths, assessed creep strain values and post-surcharge settlement for each of the sub-layers have been summarised in Table 1.

It can be seen from Table 1 that the majority of the estimated post-construction settlement of 0.1 m in 20 years is from the bottom two sub-layers which, through the process of the surcharging, have in fact become virtually "normally consolidated".

Table 1: Summary of Preload Analysis Results for Example Problem from Analytical Procedure Described in Section 2

	Sub-layer	**1**	**2**	**3**	**4**
Initial Condition	Thickness (m)	2	2	2	3
	Initial Effective Stress (kPa)	5	15	25	37.5
	OCR	10	4	2	1.2
	Pre-consolidation Pressure (kPa)	50	60	50	45
After 2.5 years Preload	Degree of Consolidation (%)	93	80	70	62
	Effective Stress Achieved (kPa)	113.7	108.5	106.9	110
Final Condition after Surcharge Removal and Application of Design Load	Final Effective Stress (kPa)	83.2	93.2	103.2	115.7
	Final OCR	1.37	1.17	1.04	1.00
	Final $C_{\alpha\varepsilon}$(oc) (from Equation [1] with m=0.1, n=6	0.003	0.007	0.013	0.015
	Primary Consolidation due to applied load (m)	0.002	0.002	0.002	0.018
	Artificially aged time, “toc”	4.6E+5	65	2.1	1[(1)]
	Creep settlement in 20 yrs (m)	0.000	0.001	0.022	0.052
	Post-surcharge settlement in 20 yrs (m)	0.002	0.003	0.024	0.070

(1) Artificially aged time becomes the reference time of measuring creep (i.e. t_p =1 year used for this example) due to final effective stress being higher than effective stress achieved during preloading of this sub-layer.

Sensitivity analyses carried out indicate that the assessed post-construction settlement would be 20% higher if the reference time, t_p is halved from 1 year to 0.5 year.

3.3 COMPARISON USING MESRI (1991)

The same example problem is assessed using the experimental data of Mesri (1991) as reproduced in Figures 5 and 6 of Wong (2006a). However, rather than using a trial and error approach to calculate the required preload thickness, the results from Section 3.2 have been adopted for comparison of the assessed post-construction settlement as presented in Table 2.

The interesting point to note in this comparison is that the creep strain values obtained using Mesri's approach are generally less than those using the approach adopted by the author of this paper using Equation 1, with m and n coefficients of 0.1 and 6 respectively. However, the calculated long-term creep is similar for both cases because the difference in $C_{\alpha\varepsilon(oc)}$ is offset by the difference in the treatment in equivalent time of creep commencement following surcharging. For the example considered, the assessed post-construction settlement using Mesri's approach is only 3% higher than the method described in Section 2. It should be pointed out that Mesri's data on creep strain (Mesri, 1991) do not cover the situation of OCR values less than 1.2.

In this example, we have adopted a primary rebound time, t_{pr} , of 0.5 year following removal of the surcharge, based on the assumption that during unloading, c_v would be about 5 times higher than the value for virgin compression. In Mesri's approach, a greater time delay for on-set of creep and lower post-construction creep settlement would be assessed if a longer primary rebound time is used. Conversely, higher post-construction creep settlement would result if a lower primary rebound time is used.

Table 2: Summary of Preload Analysis Results for Example Problem from Using Mesri (1991) Approach.

	Sub-layer	1	2	3	4
Initial Condition	See Table 1	Same values from Table 1 adopted			
After 2.5 years Preload	See Table 1	Same values from Table 1 adopted			
Final(1) Condition after Surcharge Removal and Application of Design Load	Final Effective Stress (kPa)	83.5	93.5	103.5	116.0
	Final OCR	1.41	1.20	1.06	1.00
	R'_s = OCR – 1	0.41	0.2	0.06	0
	$t_\ell / t_{pr} = 100(R_s')^{1.7}$	22	6.5	0.8	0
	t_ℓ based on t_{pr} = 0.5 yr (i.e. relatively quick rebound due to unloading range) (years)	11	3.3	0.4	0
	t/ t_ℓ (for t = 20 years)	1.82	6.1	50	∞
	New $C_{\alpha\varepsilon}$(oc) Mesri (1991)	0.0002	0.0006	0.004(2)	0.015(3)
	Primary Consolidation due to applied load (m)	0.002	0.002	0.002	0.011
	Creep settlement in 20 yrs (m)	0.000	0.000	0.014	0.072(4)
	Post-surcharge settlement in 20 yrs (m)	0.002	0.002	0.016	0.083

(1) Refer to Mesri (1991) or as reproduced in Figures 5 and 6 in Part 1 of this paper (Wong, 2006a) for definitions of t_ℓ, t_{pr}, R_s' etc.

(2) R'_s beyond data range presented by Mesri (1991) – value extrapolated from Mesri data as reproduced in Figure 6 of Wong (2006a).

(3) R'_s beyond data range presented by Mesri (1991) – value assumed to be the same as normally consolidated value.

(4) For $t_\ell = 0$, Mesri's equation for computing creep settlement as reproduced in Equation [6] of Wong (2006a) is undefined, and as recommencement of creep in this situation is expected to occur soon after removal of the surcharge, the reference time, 0.5 yrs from surcharge removal to opening of the road to traffic is used instead to calculate post-construction settlement in a further 20 years.

3.4 COMPARISON USING CAOS-1D (POULOS, 2004)

CAOS-1D is a one-dimensional finite difference program formulated for the consolidation analysis of soils under one-dimensional conditions, although stress influence factors with depth can be used to model the effect of two dimensional loading at a particular location say across the width of an embankment. Bjerrum's time line concept is used for the treatment of creep, but a constant ratio $C_{\alpha\varepsilon(oc)}/C_{\alpha\varepsilon(nc)}$ is used (usually the same ratio of C_r/C_c) at any particular point and time within the soil profile.

Layered soil profiles may be analysed and commencement of creep may be nominated at either a user-assigned absolute time following commencement of load application, or at a user assigned degree of consolidation. For example, if 90% consolidation is assigned as the commencement of creep, then creep will initiate at the sub-layers closest to drainage boundaries. The latter option is used for the comparison study, and the results from the CAOS-1D analysis indicate the following:

- Degree of consolidation after 2.5 years preload period = 73%
- For a preload thickness of 6.4 m, settlement during the preload period of 2.5 yrs = 1.05 m
- Rebound after unloading to the design embankment height of 3 m = 0 m
- After removal of the surcharge and 8 kPa of reduced live load applied, post-construction settlement from 3 yrs to 23 yrs = 0.07 m.

The results of the CAOS-1D analysis during the preloading phase are similar to those calculated using the procedures described in Sections 3.2 and 3.3, but the post-surcharge creep was computed to be 30% less. The author believes that this difference is in part caused by the use of a constant $C_{\alpha\varepsilon(oc)}/C_{\alpha\varepsilon(nc)}$ ratio in the program formulation. Closer agreement would have resulted if a $C_{\alpha\varepsilon(oc)}/C_{\alpha\varepsilon(nc)}$ ratio less than C_r/C_c was used.

A different result would also be obtained by CAOS-1D if creep is assumed to start at a lower percentage consolidation (e.g. 80% instead of 90%), which will result in higher settlement during the preload period and lower post-preload creep settlement.

3.5 PLAXIS ANALYSIS USING SOFT SOIL CREEP MODEL

PLAXIS (Version 8, 2002) has a Soft-Soil-creep model that utilises a form of strain rate controlled time-dependent consolidation and creep analysis that also incorporates concepts of Modified Cam-clay and viscoplasticity. The required input parameters are derived from conventional laboratory consolidation parameters as follows:

Modified Compression Index $$\lambda^* = \frac{C_c}{2.3(1+e_o)} = 0.13 \text{ (for this example)} \quad \mathbf{(15)}$$

Modified Swelling Index $$\kappa^* = \frac{2}{2.3}\frac{C_r}{(1+e_o)} = 0.026 \text{ (for this example)} \quad \mathbf{(16)}$$

Modified Creep Index $$\mu^* = \frac{C_\alpha}{2.3(1+e_o)} = 0.00652 \text{ (for this example)} \quad \mathbf{(17)}$$

PLAXIS also allows the user to either define the initial OCR profile, or to generate the initial OCR profile by allowing the soil to creep over a user-specified geological time. To account for over-consolidation effects other than those generated by creep under self-weight, it is possible to select the OCR profile option (e.g. to account for erosion, desiccation, chemical bonding etc), and in addition, allow the soil profile to initialise over a geological time which will be nominated as t_i in this paper. This latter option has been adopted for the example problem to demonstrate that depending on the selection of t_i, PLAXIS will generate different results and may over-estimate the creep settlement if t_i is too low.

The PLAXIS analysis results are presented in Figure 4 together with those from the CAOS-1D analysis. It can be seen that when t_i is set to zero, the calculated settlement during the preload period of 2.5 years is about 30% higher than those calculated using conventional consolidation theory, and the post-surcharge settlement in 20 years is almost double those calculated using the methods described in Sections 3.2 to 3.4. With increasing t_i, the calculated settlement during preload, and the post-surcharge settlement reduce, and become 15% and 30% higher than those calculated using the procedure described in Section 3.2 when a t_i value of 10,000 years is used.

The difference in results caused by the use of different t_i values highlights the need for appreciating the importance of the geological time history, and the way in which computation methods deals with this issue. The dependency of the results on t_i is not unexpected when the more easily understood time line concept is used.

Another interesting observation from the PLAXIS analysis results is the relatively large post-surcharge settlement for this example. The majority of the settlement was indeed from the lower soil profile which did not achieve sufficient consolidation during the preloading stage, and this supports the observations made by the author using the stress path/time line approach.

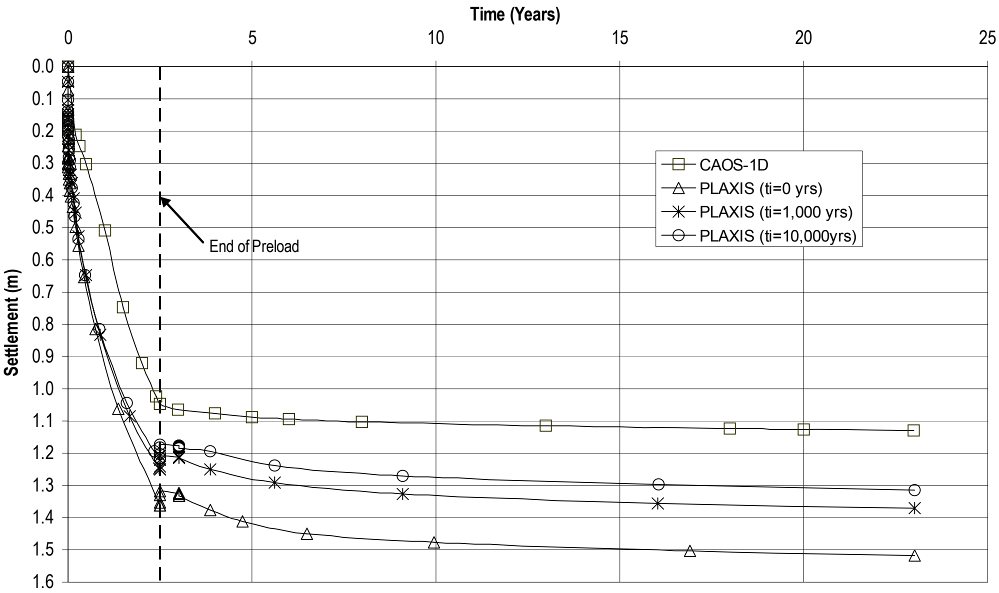

Figure 4: Results of Numerical Analysis (CAOS-1D & PLAXIS).

4 CONCLUSION

A modified form of Bjerrum's time line model for design of preloads has been developed with the introduction of stress level and stress history dependency based on the discussions given in Wong (2006a). A worked example has been used, and compared with other design methods (Mesri, 1991, Poulos, 2004, and the Soft-Soil-Creep Model of PLAXIS Version 8, 2002). The results indicate the following for the example problem described in this paper:

- Calculated post-construction settlements in 20 years for the various methods are ±30% compared to the analytical spreadsheet approach outlined in this paper.
- The method of Mesri (1991) gives close agreement (3% difference) although the treatment of creep strain rate and equivalent creep commencement time are different between the two methods.
- CAOS-1D by Poulos (2004) gives the lowest post-construction settlement, which is partly caused by the use of a constant $C_{\alpha\varepsilon(oc)}/C_{\alpha\varepsilon(nc)}$ ratio, rather than a variable ratio depending on OCR as suggested by Wong (2006a).
- PLAXIS (Version 8, 2002) gives the highest consolidation during preloading and post-construction settlement, and the results are dependent on the initial geological time, t_i , used to initialise the soil profile in addition to the OCR profile used. The greater t_i, the lower will be the calculated settlement due to the geological time history dependency of creep.

More importantly, the analysis results support the following observations:

- Post-construction settlement of preloaded soft ground is highly dependent on initial and final stress levels and OCR. This is particularly important for embankments with large anticipated settlements due to significant fill loading.
- Use of the time line or "artificial aging" principle in preload design can provide readily understood concepts and reasons for significant post-construction settlement following preloading in situations where a significant portion of the soft soil profile has not been preloaded to sufficiently high OCR.
- Special care needs to be given in preload design of thick soft soil deposits, particularly if only one way drainage is available. This may also be the case even if wick drains are used, and if the lower part of the soft soil profile is not adequately drained for reasons such as smearing, kinking or clogging of the wick drains.

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