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Estimation of pre-compression parameters in the acceleration of consolidation settlement

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Abstract: Pre-compression by preloading is used to accelerate the consolidation settlement of a site ahead of construction so that post-construction settlement would be minimal. The principal aim of the technique is to remove the primary consolidation settlement anticipated under the proposed load with or without partial compensation for secondary compression so that post-construction settlement would consist of a small re-compression and secondary compression. In this paper, the scope of pre-compression is expanded to include partial removal of primary consolidation as a possible settlement management option. Modifications and simplifications are introduced into parameter estimation for design to deal with pre-compressions intended to remove any degree of the primary consolidation and those that go beyond the primary consolidation stage. This provides foundation engineers the flexibility to evaluate different pre-compression load and duration options under different settlement regimes and their implications. A numerical example is used to demonstrate and verify the modifications.

Keywords: Pre-Compression, Primary Consolidation, Settlement, Surcharge Load

1. Introduction

Pre-compression offers the opportunity for large post-construction settlement of structures founded on highly compressible normally consolidated clay layers to be minimized in order to avoid failure due to excessive settlement. The process, also known as preloading, uses temporary loading to accelerate the consolidation of a site ahead of construction so that when the actual structure is built, very little consolidation settlement would take place. The principle is to remove primary consolidation so that post construction settlement would consist essentially of a small re-compression and secondary compression only. Because pre-compression renders the soil layer effectively over-consolidated on removal of the temporary load, the technique has the added benefit of slowing down the rate of secondary compression since the magnitude of secondary compression in a given time, is generally smaller in over-consolidated than in normally consolidated clays [1-3].

Interest in and the use of pre-compression have been motivated largely by the scarcity of advantageously-located land with good foundation conditions and also the high costs associated with reclamation of marginal lands compared to other alternatives [4]. Where there are time constraints, the rate of pre-compression may be augmented by the installation of vertical sand drains to induce both vertical and radial drainage so that a site is brought to use much sooner. The use of the pre-compression technique to deal with soft sub-soils where excessive settlements posed a challenge to construction and engineering structures has been well reported in the literature [4-9].

The total load to which the site is preloaded would consist of the load to be imposed on the compressible layer by the anticipated structure and a surcharge load whose magnitude is determined by the amount of settlement intended to be removed within a given time frame; shorter pre-compression times would require larger surcharge loads. The practice in managing the settlement has been to remove the entire primary consolidation anticipated under the proposed load plus, in some cases, a portion of secondary compression. In principle, however, the scope of settlement removal could be defined over a much wider range of possibilities, including even partial removal of the primary consolidation settlement, provided that this would lead to tolerable settlements. It is believed that the ability to explore a wider scope of settlement removal, such that even partial removal of the primary consolidation settlement also became an option for managing settlements, could be helpful to design decisions when there are time, site, and resource constraints.

Based on the theory of consolidation, Johnson [4] derived expressions and presented a design procedure by which pre-compression load and time could be estimated from the consolidation parameters of the compressible layer. The underlying assumption was that the pre-compression load would be sustained until the total primary consolidation settlement anticipated under the proposed load has been removed. As a result of this assumption, the expressions derived thereof are inapplicable to the design of pre-compressions intended to remove only a portion of the primary consolidation settlement. In this paper, modifications and simplifications are introduced into pre-compression design expressions to make it possible to deal with pre-compressions that remove any degree of the primary consolidation settlement as well as those that go beyond the primary consolidation stage into secondary compression. The major thrust of the paper, therefore, is the estimation of the magnitude of the surcharge load to be employed in the pre-loading process.

2. Settlement Consideration

2.1. Fundamental Theory

Figure 1 shows the loading and associated consolidation settlement curves for the proposed structural load (Curve 1) and pre-compression load (Curve 2) [4].

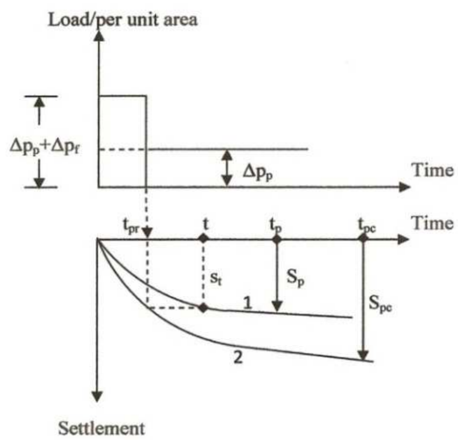

Figure 1. *Load- and settlement-time curves for pre-compression and normal loads.*

Associated with the curves are the following parameters;

Δp_p = proposed load increase per unit area
Δp_f = surcharge load per unit area
t_p = end of primary consolidation under proposed structure
t_{pc} = end of primary consolidation under pre-compression load
t_{pr} = time of pre-compression
s_t = settlement at any time t under proposed load
S_p = maximum primary consolidation settlement under proposed structure
S_{pc} = maximum primary consolidation settlement under pre-compression load

For a normally consolidated clay layer, the maximum primary consolidation settlements associated with the loadings represented by Curves 1 and 2 are, respectively,

$$S_p = \frac{C_c H_c}{1+e_o} log \frac{p_o+\Delta p_p}{p_o} \quad (1)$$

and,

$$S_{pc} = \frac{C_c H_c}{1+e_o} log \frac{p_o+[\Delta p_p+\Delta p_f]}{p_o} \quad (2)$$

where,

C_c =compression index of the clay layer
e_o =initial void ratio of the layer
H_c =thickness of the layer
p_o =initial effective overburden pressure in the middle of the clay layer.

2.2. Removal of any Degree of Primary Consolidation

At time $t \le t_p$, let the settlement (s_t) under the proposed load (Curve 1) correspond to the degree of consolidation U_t. From consolidation theory, s_t may be evaluated as

$$s_t = U_t S_p \quad (3)$$

This amount of settlement may be achieved by pre-compression (Curve 2) in a much shorter time $t = t_{pr}$. Let the pre-compression process at time $t = t_{pr}$ be at a degree of consolidation U_{pr}, then;

$$U_{pr} = U_t S_p / S_{pc} \quad (4)$$

Substitution of Eqs. (1) and (2) into Eq. (4) results in the following expression for U_{pr} ;

$$U_{pr} = \frac{U_t log\left(1+\frac{\Delta p_p}{p_o}\right)}{\log\left[1+\frac{\Delta p_p}{p_o}\left(1+\frac{\Delta p_f}{\Delta p_p}\right)\right]} \quad \text{for } 0< t \le t_p \quad (5)$$

Equation (5) indicates that up to the end of primary consolidation, the degree of consolidation under pre-compression is dependent on the pre-loading condition and the amount of primary consolidation settlement to be removed.

2.3. Partial Removal of Secondary Compression

Partial removal of secondary compression should become a design option only when removal of the entire primary consolidation would not suffice to bring settlements to within tolerable limits. For such a situation, consider Curve 1 in Fig. 1 and the settlement at any time t beyond t_p (end of primary consolidation). The settlement would consist of the entire primary consolidation settlement and a portion of secondary compression. Hence,

$$s_t = S_p + \Delta H_{sec} \quad (6)$$

$$\Delta H_{sec} = c_\alpha H_p log(t/t_p) \quad (7)$$

where,
c_α = coefficient of secondary compression of the layer
H_p = thickness of compressible layer at the end of primary consolidation (=H_c-S_p)
ΔH_{sec} =portion of secondary compression being removed

The required degree of consolidation under pre-compression load that will achieve equivalent settlement may be given as,

$$U_{pr} = \frac{S_p + c_\alpha H_p log(t/t_p)}{S_{pc}} \quad (8)$$

where,
U_{pr} =degree of consolidation under pre-compression load at time $t \geq t_p$.

Substitution of Equations (1) and (2) in Eq. (8), results in the following expression for U_{pr} when $t \geq t_p$ (see [4] and [10]);

$$U_{pr} = \frac{\left(1 - c_\alpha log\frac{t}{t_p}\right) log\left(1 + \frac{\Delta p_p}{p_o}\right) + \frac{c_\alpha}{C_c}(1+e_o) log\frac{t}{t_p}}{log\left[1 + \frac{\Delta p_p}{p_o}\left(1 + \frac{\Delta p_f}{\Delta p_p}\right)\right]} \quad (9)$$

3. Estimation of Pre-Compression Parameters

3.1. Overview of Method

The method for estimating either the surcharge load or time, elaborated by Johnson [4], covers the specific case of U_t =1 in Eq. (5) when the pre-compression process is intended to eliminate the entire primary consolidation settlement expected under the proposed load. The procedure involves the use of two charts; U-load ratio curves and U-T_v curve reproduced in this paper as Figs. 2 and 3, respectively. The U-load ratio curves (Fig. 2) as re-plotted by Das [11] were originally presented by Johnson [4] based on a version of Eq. (5) without the parameter U_t for various combinations of surcharge intensity $\Delta p_f/\Delta p_p$ and permanent loading ratio $\Delta p_p/p_o$. The U-T_v curve (Fig. 3), which expresses the variation of the mid-plane degree of consolidation in the compressible layer with the time factor for consolidation, is taken conservatively to represent the average degree of consolidation during pre-compression as recommended by Johnson [4] due to the difficulty associated with the variation of the degree of consolidation across the depth of the compressible layer as a result of the position of the drainage surface. The two charts (Fig. 2 and Fig. 3) may be used together to obtain any of the pre-compression parameters (surcharge load or time). In practice, the magnitude of one of the parameters (more often the time) is pre-determined and the other estimated. The time factor (T_v) for pre-compression is determined from standard expression ($T_v = c_v t_{pr}/d^2$) using the pre-compression time. The T_v value so determined is then used to enter Fig. 3 to determine U which is in turn used in Fig. 2 to determine the surcharge intensity from which the surcharge load is evaluated. The process is reversed if the duration of pre-compression is required for a pre-determined surcharge load.

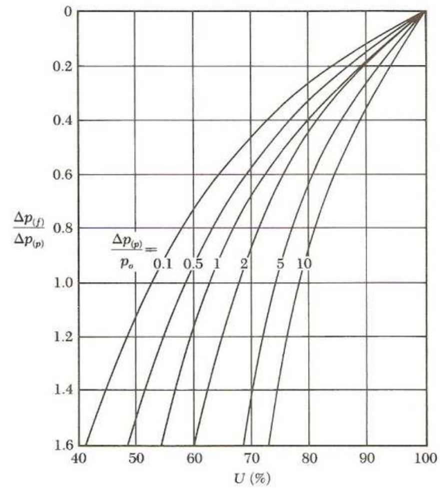

Fig 2. Plot of $\Delta p_f/\Delta p_p$ against U for various values of $\Delta p_p/p_o$ [4].

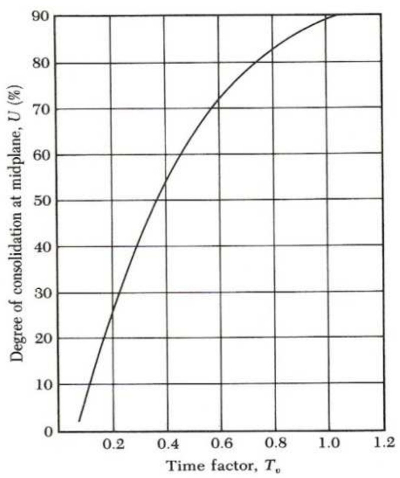

Fig 3. Mid-plane degree of consolidation versus Tv in pre-compression [11].

3.2. Proposed Modification and Simplification

Figure 2 represents a specific case of the pre-compression process, i.e., removal of total primary consolidation settlement and is, therefore, inapplicable to designs intended to remove only a portion of the primary consolidation settlement. This limitation may be addressed by the use of Eq. (5) which contains the parameter U_t that takes care of the degree of primary consolidation settlement desired to be removed by the pre-compression process. For further simplification, let the permanent loading ratio be denoted as a, that is,

$$a = \Delta p_p/p_o \quad (10)$$

Equation (5) can then be re-written as:

$$U_{pr} = \frac{U_t log(1+a)}{log[1+a(1+\Delta p_f/\Delta p_p)]} \quad (11)$$

To obtain the surcharge load required for the pre-compression process directly, Eq. (11) may be simplified and re-arranged to obtain,

$$\Delta p_f = \frac{\Delta p_p(1+a)}{a}\left[(1+a)^{U_t/U_{pr}-1} - 1\right] \quad (12)$$

Even though Eq. (12) overcomes the limitation inherent in Fig. 2, its applicability ends at the primary consolidation stage. To deal with pre-compressions that go into secondary compression, Eq. (9) must be used but simplifications are needed to arrive at a direct expression for the surcharge load. To simplify the equation, let the following be introduced;

$$\beta = c_\alpha(1+e_o)/C_c \quad (13)$$

$$\delta = \left(1 - c_\alpha log\left[t/t_p\right]\right) \quad (14)$$

Substitution of Equations (10), (13) and (14) into Eq. (9) results in the following expression for the degree of consolidation of pre-compression designed to remove a portion of secondary compression;

$$U_{pr} = \frac{\delta log(1+a) + \beta log(t/t_p)}{log\left[1+a(1+\Delta p_f/\Delta p_p)\right]} \quad (15)$$

For $t \geq t_p$, Eq. (15) may be simplified further and re-arranged to obtain the surcharge load directly as:

$$\Delta p_f = \frac{\Delta p_p(1+a)}{a}\left[(1+a)^{\delta/U_{pr}-1}(t/t_p)^{\beta/U_{pr}} - 1\right] \quad (16)$$

It is to be noted that at the end of primary consolidation, $t=t_p$, $U_t= 1$, $\delta=1$, and Eq. (16) reduces to Eq. (12).

By setting the value of t equal to the useful life of the construction in Eq. (16), the pre-compression could be designed to eliminate the entire secondary compression and, hence, practically all settlements to be expected during the life of the construction but this would, by no doubt, result in uneconomical preloads and possibly ground instability and other problems during the process. It may, therefore, suffice to design the pre-loading to remove only a portion of the secondary compression that would result in tolerable settlements should removal of the entire primary consolidation turn out to be inadequate. Computations could easily be carried out to determine the limit of t values that would achieve this, but values of t/t_p equal to 10 or 15 are suggested. A value of t/t_p=10 covers one cycle of secondary compression beyond the end of primary consolidation.

To apply Eq. (12), the proportion of primary consolidation settlement to be removed expressed in terms of degree of primary consolidation (U_t) and the duration of pre-compression (t_{pr}) must first be decided upon; the time factor (T_v) is then calculated and the value of the corresponding degree of consolidation of pre-compression to achieve this is obtained with the help of Fig. 3. The value of the degree of consolidation is then input into Eq. (12) as U_{pr} to enable the computation of the surcharge load Δp_f directly. On the other hand, if the duration of pre-compression is required for a given surcharge load and targeted level of primary consolidation settlement removal, U_{pr} is evaluated using Eq. (11) and then Fig. 3 used to establish the corresponding value of T_v from which $t=t_{pr}$ is calculated.

For pre-compressions that include partial removal of secondary compression, prior settlement computations by standard procedure would be necessary to determine the end of primary consolidation (t_p), the total settlement (primary and secondary) anticipated under the proposed load and the amount of secondary compression to remove. This would make it possible to arrive at a suitable value for the time ratio (t/t_p) to be input into Eq. (16). From the pre-determined surcharge duration, the time factor (T_v) is calculated in the usual manner and the value used to enter Fig. 3 to obtain U_{pr} which in turn is used together with the t/t_p value and other relevant soil data to evaluate the surcharge load using Eq. (16). The procedure is reversed if the surcharge load is pre-determined and the duration of pre-compression is required.

The numerical example that follows demonstrates the use of the existing and modified expressions and simplifications for estimating pre-compression loads.

3.3. Numerical Example

A pre-compression project is intended to preload the site of a proposed warehouse, which is underlain by 6m thick normally consolidated clay, for a period of 10 months in order to minimize post construction settlement. The average effective overburden pressure of 200kN/m^2 at the middle of the clay layer is expected to increase by 100kN/m^2 when the warehouse is built. Given that the clay layer is drained both at the top and bottom and has C_v=0.36m^2/month, C_c=2.13, c_α=0.022, e_o=1.35, determine the magnitude of surcharge load required for the preloading process, if:

i. the entire primary consolidation is to be removed.
ii. removal of 75% of the primary consolidation would lead to tolerable settlement.
iii. removal of one cycle of secondary compression beyond primary consolidation is necessary.

3.3.1. Removal of entire primary consolidation

a. Solution by existing procedure

This procedure combines the use of Figs. 2 and 3 to determine the surcharge load. From the data,

t_{pr}=10months
C_v=0.36m^2/month.
d=3m,
p_o=200kN/m^2,
Δp_p=100kN/m^2.
$a = \Delta p_p/p_o = 0.50$,
Hence, $T_v = 0.40$
From Fig. 3, for T_v=0.40, U=U_{pr}= 54% (or U_{pr} =0.54)
At U=54%, and $\Delta p_p/p_o = 0.50$, Fig. 2 gives
$\Delta p_f/\Delta p_p = 1.23$
Hence, Δp_f =123kN/m^2.

b. Solution by modified procedure

From the data and previous calculations,

$U_t=1$, $U_{pr}=0.54$, $a=0.5$, $(U_t/U_{pr}-1)=0.852$

Using Eq. (12),

$$\Delta p_f=\frac{(100)(1.5)}{0.5}(1.5^{0.852}-1)=123.8kN/m^2$$

3.3.2. Removal of 75% primary consolidation

Solution by modified procedure

From the data and previous calculations, $U_t=0.75$, $U_{pr}=0.54$, $a=0.5$

$(U_t/U_{pr}-1)=0.389$,

Using, Eq. (12),

$$\Delta p_f=\frac{(100)(1.5)}{0.5}(1.5^{0.389}-1)=51.24kN/m^2$$

3.3.3. Partial removal of secondary compression

From the data and previous calculations,

$t/t_p=10$, $a=0.5$, $U_{pr}=0.54$, $\delta=0.978$, $\beta=0.024$

$(\delta/U_{pr}-1)=0.811$, $(\beta/U_{pr}-1)=0.044$

Using Eq. (16),

$$\Delta p_f=\frac{(100)(1.5)}{0.5}[(1.5)^{0.811}10^{0.044}-1]$$

$$\Delta p_f=161.24kN/m^2$$

4. Discussion

The first part of the numerical example showed almost excellent agreement between the existing and modified procedure with the latter presenting a much simpler evaluation; the small and negligible difference between the results of the two procedures being due entirely to the level of accuracy to which values from the relevant charts were read. In the case of partial removal of primary consolidation, the solution whereby Figs. 2 and 3 are combined was not possible, as Fig. 2 was developed solely for total removal of primary consolidation settlement; only the modified procedure could be used to arrive at the magnitude of the surcharge load. In addition, the modified procedure did not require the use of Fig. 2. In the case of pre-compressions that go into secondary compression, the simplification provided by Eq. (16) made it possible to evaluate the surcharge load directly using the relevant secondary compression data, pre-compression time, and degree of consolidation.

As demonstrated above, only Fig. 3 was actually required for any of the pre-compression load computations. The benefits of the modifications introduced are the possibility to design pre-compressions to cover partial removal of the primary consolidation and the simplicity of design computations. With the scope of pre-compression expanded by the current modifications to include partial removal of the primary consolidation as a possible option, foundation engineers now have a much wider choice of options to consider in terms of settlement removal and accompanying cost, time, and potential ground stability implications.

Of course it has to be understood that in situations where the pre-compression has to go beyond removal of primary consolidation because a large amount of settlement is anticipated under the proposed structural load, the usefulness of the approach developed in this paper would be limited only to the simplifications introduced into the computational process for the relevant pre-compression parameters. Furthermore, the methodology and analysis procedure used did not consider the contribution of installation of sand drains to the pre-compression process. Because sand drains accelerate the settlement process by augmenting lateral drainage of the compressible layer, their use as part of pre-compressions is aimed at shortening the preloading time and possibly reduce the magnitude of the preload required. Further work is required to deal with parameter estimations in pre-compressions that are designed to remove only part of the primary consolidation settlement using sand drains to augment the process.

5. Conclusion

Pre-compression by preloading provides opportunity for excessive settlements anticipated under structures to be founded on sites underlain by highly compressible soils to be managed prior to the actual construction so that the safety and integrity of the structure would be assured. The magnitude of the pre-compression load is defined by the amount of the anticipated settlement to remove within a given time frame. Traditionally, the technique has tended always to focus on the removal of the entire primary consolidation settlement, with or without partial compensation for secondary compression. As a result, the expressions for determining pre-compression parameters are limited in application as they are based on the elimination of the total primary consolidation settlement and, therefore, cannot deal with partial removal of primary consolidation. This paper introduced some modifications and simplifications to the existing method of estimating pre-compression parameters to overcome this limitation. It is believed that partial removal of the primary consolidation could also be an option in settlement management by pre-compression, provided it would lead to tolerable settlements. Verification of the proposed modification and simplifications was demonstrated through a numerical example. The methodology and analysis procedure used in the paper, though, did not consider pre-compressions which use sand drains to accelerate the drainage process. Further work is, therefore, recommended in that direction to expand the scope of the subject.

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