

Precompression of Soft Soils by Surcharge Preloading: Some Common Pitfalls and Misunderstood Fundamentals

By: Y. Bhg. Dato Engr. Assoc. Prof. Ramli bin Mohamad, *MIEM, P. Eng.*

It is quite common for designers of embankments on soft ground to specify surcharge preloading to compensate for or eliminate post-construction settlements. Properly designed and executed, the method can be a powerful and economical way to build high embankments on soft ground. It certainly represents a much cheaper alternative to solutions that involve constructing a rigid foundation such as a piled slab or stone columns beneath the embankment. However, there have been many cases where post-construction settlements have continued after completion of surcharge preloaded embankments and this has led to some erosion of confidence in the method.

In essence, the method is simple. To build an embankment to a final height, H_f that would not settle or would settle very little after it has been built, the embankment is first built to a height $H_s + H_f$ that is higher than the desired final height and is left to settle for a period T_p under the load intensity $p_f + p_s$ due to this extra height of fill. At the end of the preloading period T_p , the surcharge fill of height H_s is removed, causing the soft soil to be unloaded, resulting in elimination or a huge reduction in post-construction settlements under the final height of embankment H_f .

Most or all of the primary settlement and some of the secondary settlement that would have occurred under the final embankment height alone are forced to take place under the surcharge loading and, in addition, the soil beneath the embankment becomes overconsolidated or stiffer. Figure 1 illustrates the key elements of the concept of surcharge preloading to compensate for primary and secondary settlements.

Usually, the aim is to eliminate 100% of the primary consolidation settlement and enough secondary settlement such that the residual settlement is within acceptable performance limits. The residual settlement for a given length of time after construction can be estimated as the remaining secondary settlement that occurs during the required time after the eliminated equivalent time of secondary compression has elapsed.

COMMON PITFALLS

The method has not always been applied successfully. The author has had the opportunity to examine some of the cases where the method of surcharge preloading has failed to arrest post-construction settlements. Some highway embankments have kept settling and required regular

topping up to maintain their design levels, and such topping up have caused more severe settlements. The author finds that the usual reason for the ineffectiveness of the method is not in the method itself, but in the improper application of the method caused by a lack of understanding of the fundamentals associated with the method. Among the common mistakes made by designers when applying the method of surcharge preloading are:

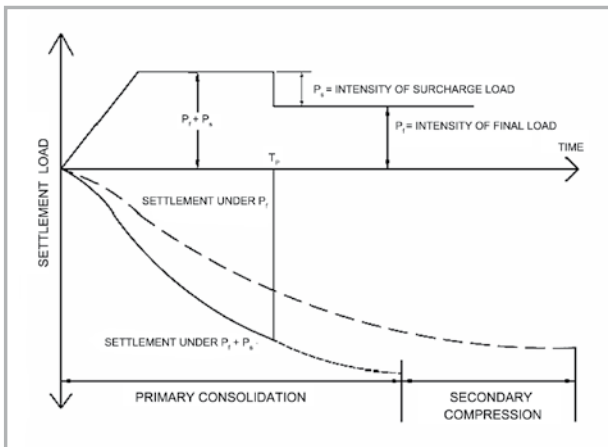


Figure 1: Concept of surcharge preloading to compensate for primary consolidation settlement and secondary compression

- **Inadequate site investigation and laboratory testing.** A thorough site investigation and laboratory testing programme should be done to obtain the relevant engineering parameters for use in the design. In particular, the subsurface profile should be determined as accurately as possible, together with the geological history of the site. The engineering properties of importance are the maximum past pressures σ_{vc}' , compression and recompression indices C_c and C_{cr} , the coefficient of consolidation C_v , the secondary compression index C_a and the undrained shear strength s_u together with an estimate of the relationship between s_u and effective overburden stress before applying the method of surcharge preloading. These parameters usually vary with the depth within a soil layer and it is important to plot the data against the depth to provide a clear picture of their variability within the soils beneath the embankment that will be built.
- **Inadequate surcharge or no removal of surcharge.** This is a rather common flaw. Engineers must bear in mind that one of the critical parameters in the design is surcharge ratio, *i.e.* the ratio of the surcharge load, p_s to the final load, p_r . The surcharge load p_s represents the amount of surcharge that is removed at the end of the preloading period. Often, the settlement that takes place during preloading is not taken into account by designers. This settlement can be substantial and may even exceed the initial height of the surcharge. Thus it is important that in estimating the values of p_s and p_r the settlements are taken into account. There have been cases where at the end of the preloading period, the settlements that have occurred have brought the embankment level to the desired finished level, and the designer or the resident engineer then accepts that there is no surcharge to be removed. This is equivalent to having a value of $p_s = 0$, which will certainly make the embankment equivalent to one that has not been surcharge preloaded. There must be an adequate amount of surcharge that is removed at the end of the preloading period for the method to be effective.
- **Inadequate stability during construction.** The construction of an embankment on soft soil too rapidly can cause the embankment to collapse through failure of the base. Most soft soils will gain strength as it is loaded provided the excess pore pressures that develop due to the application of the external load are allowed to dissipate, *i.e.* as the effective stresses applied to the soft soils increase or as the void ratio of the soft soils decrease. It may be necessary to provide basal georeinforcement to ensure stability during construction for total heights (inclusive of surcharge) that exceed the safe height that the soft soil can support on its own. Once an embankment can be built on soft ground, it will usually remain stable thereafter if no additional loads are placed on it, because the shear strength of the soft soils underneath can only gain in strength as time goes by.
- **Designing for compensation of primary settlement only.** Secondary settlements can be large and it is possible to design a surcharge preloading scheme to eliminate all of the primary settlement and much of the secondary settlement that would occur under the final load, but many designers seem to prefer to ignore secondary settlements. Secondary compression is a strange thing – it requires primary consolidation to occur first under a given load, but the load intensity does not appear in the computations. The magnitude of secondary compression depends on the time elapsed after completion of the primary consolidation, the void ratio and the thickness of the soil layer at that point in time, but not on the intensity of the applied load. The drainage path during secondary compression also does not appear in the computations.
- **Removing surcharge too early.** For a set of given conditions, the optimum time for the removal of surcharge should be determined based on the desired post-construction performance of the embankment. Removing the surcharge too early will result in the soft soils not achieving sufficient settlement to compensate for the primary and secondary settlements that would occur under the final load.

- **Inadequate instrumentation, monitoring and back analysis during construction.** In designing and constructing embankments on soft ground using the method of surcharge preloading, it is very important to adequately and continuously measure and interpret data related to settlements, lateral movements, ground heave and pore pressures within the soft soils beneath the embankment. The purpose is to measure settlements and other ground movements, to assess stability during construction, to verify the parameters that are used in the design, to assess the effectiveness of vertical drains if these are used, to make adjustments in loading rates and help the designer determine if the surcharge levels need to be varied, and to help the designer determine the most appropriate point in time to remove the surcharge.

FUNDAMENTAL PARAMETERS

The success of a surcharge preloading scheme depends heavily on the proper acquisition, interpretation, usage and control of several key parameters. The engineering parameters that are of importance and how they affect a surcharge preloading scheme need to be understood for achieving a good and effective design. These are briefly discussed:

- γ_b : Bulk density, a simple property that is often assumed, can be the cause of fairly significant problems. The parameter is required for the calculation of in-situ effective vertical stress, p_{f0} at the centre of a soft soil layer before the application of any load. The parameter p_{f0} in turn, appears in the computations for surcharge preloading and, hence, it is important that this parameter is obtained as accurately as possible using measurements of densities of undisturbed samples rather than simply assuming a density.
- C_c, C_a : These two parameters are necessary for the computation of primary consolidation and secondary compression settlements. These parameters are usually obtained from laboratory consolidation tests on high quality undisturbed samples. Correlations are also available in the literature, but if they are to be used, it is best to trust the ones that have been developed based on local data.
- C_c/C_a : This ratio is important in determining how much secondary settlement can be eliminated for a given scheme. The higher the ratio, the more secondary settlement can be eliminated in a given preloading period. Put in another way, for a given preloading period, it is possible to estimate the equivalent time of secondary compression that will be eliminated. Or one can set the equivalent time of secondary consolidation that one wishes to eliminate, e.g. 10 years, 50 years or 100 years, and then use the ratio to determine other parameters for the scheme such as the surcharge level and preloading period. Both C_c and C_a can be obtained from laboratory consolidation tests on high quality undisturbed samples. The author's experience with soft clays along the west coast of Peninsular Malaysia indicates that this ratio is typically in the range from about 30 to over 100, hence it is best to obtain this ratio from consolidation tests on high quality samples obtained from the actual site.
- U_{f+s} : Usually, the aim of a design would be to completely eliminate primary consolidation settlement under the final load p_f and an equivalent number of years of secondary compression. This is done by preloading to a predetermined degree of consolidation under surcharge + final load, U_{f+s} . For a given set of other parameters, the higher this value is, the more settlement is eliminated under the final load. In most cases, designers try to aim for $U_{f+s} = 90\%$, but it does not need to be always so. If time is limited and stability can be enhanced by using basal georeinforcement, it may be possible to apply the surcharge preload to achieve a degree of consolidation U_{f+s} less than 90%.
- p_s/p_f : The surcharge ratio is the parameter that the designer has full control of. For a given set of other parameters, this ratio determines the duration of preloading that is needed to eliminate a specified amount of post-construction settlement. During construction as well, this ratio can be varied depending on the observations of the site instrumentation data and the back analyses of those data. It is emphasised again that this ratio must be calculated by taking into account the settlements that actually occur on site under the surcharge loading. This ratio should not be zero as that would represent the case of no surcharge preloading. Surcharge must be removed for the method to work.
- T_p : The preloading duration, T_p is usually controlled by the construction programme. Typical preloading durations range from three months to 12 months or more. Obviously, the longer the available time, the better it is, since the surcharge ratio can be kept lower or a greater amount of secondary compression can be eliminated. With the use of closely spaced prefabricated vertical drains, the preloading duration can be relatively short even for deep layers of soft ground. However, care should be taken in the selection, detailing and installation of prefabricated vertical drains if very large settlements are expected. If the preloading duration is limited due to a tight construction programme, the designer may be forced to use a high surcharge ratio which may in turn force him to incorporate measures such as counterweight berms, basal georeinforcement or other means to ensure stability during construction.
- s_u/σ_{v0}' : The relationship between undrained shear strength and effective vertical stress can be obtained from both field tests such as the vane shear tests or from laboratory tests such as the consolidated-undrained triaxial tests. It is important to have this relationship for the soft soils that are being loaded by the embankment as it will help the designer stage the construction to take advantage of the gain in strength of the soft soils as the embankment is built. It is also important to note that the potential slip surface in a base failure extends well beyond the edge of the embankment and the gain in strength outside the zone loaded by the main embankment body is not the same as directly beneath the embankment, and this has to be taken into account in the stability analyses.

Based on the analysis of field vane shear data for soft clays along the west coast of Peninsular Malaysia, the

author has found that the relationship $s_u/\sigma_{v0}' = 0.259OCR^{0.78}$ gives a reasonable approximation of the undrained shear strength (Ramli Mohamad, 1992)[1].

- **c_v and c_h :** The coefficient of consolidation determines the rate of consolidation and, hence, the time required to achieve a specified degree of consolidation. If prefabricated vertical drains are used, the coefficient of horizontal consolidation, c_h applies. Usually the parameter is used to determine the spacing of the prefabricated vertical drains to achieve a desired time for a specified degree of consolidation. What is of main interest is the time required for a specified degree of consolidation under the surcharge loading. The coefficient of consolidation is determined from laboratory consolidation tests, but c_h can also be estimated directly in the field through pore pressure dissipation tests using appropriately-tipped cone penetration equipment. In the absence of c_h data, it is customary to estimate

c_h as a multiple of c_v , typically two to four. Based on the author's experience, typical values of c_v from laboratory tests on soft clays along the west coast of Peninsular Malaysia range from $0.3m^2/yr$ to about $2m^2/yr$, although it must be warned that values of c_v obtained from laboratory tests are heavily affected by sample disturbance, being lower with increasing sample disturbance.

CONCLUSION

The fundamentals and some pitfalls associated with the method of surcharge preloading to precompress soft soils are briefly discussed. This paper is not intended to delve into the actual methods of analyses available for designing surcharge preloading schemes on soft soils, but more of an advisory note to engineers who are already familiar with the concept, but may not be fully conversant with the fundamentals associated with the method and may also not be fully aware of all the pitfalls that are associated with the method. Hence, no formula or step-by-step guide is given

for the application of the method. Readers should be able to find such formulas and guides in established geotechnical publications as the method has been in existence since the 1970s, e.g. Johnson (1970)[2]. ■

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About Author:

*Y. Bhg. Dato' Engr. Assoc. Prof. Dr Ramli bin Mohamad is a director of Straits Consulting Engineers Sdn Bhd, a civil engineering consulting firm and Macroworks Sdn Bhd, an enterprise management consulting firm.