Reappraisal of Surcharging to Reduce Secondary Compression

Remise en cause de l'imposition de frais supplémentaires pour réduire la Compression secondaire

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ABSTRACT: For structures on soft soils with relatively high secondary compression characteristics, post-construction settlement may be excessive so that application of surcharging may be called for to reduce secondary compression. The principle of surcharging is simple, but the post-surcharge secondary compression behavior requires further study. This paper looks into effects of surcharging loading history on post-surcharge secondary compression characteristics of soils. Current knowledge on this subject is primarily based on unloading from surcharge stress to permanent stress. There could be other types of surcharging stress history. For example, all preloads, including permanent load and surcharge load, are removed before the permanent load is reapplied. Laboratory data of secondary compression with different surcharging stress history are presented and discussed. These data provides useful information for understanding the post-surcharge secondary compression behavior of soils.

RÉSUMÉ : Pour les structures sur des sols mous avec des caractéristiques de compression secondaire relativement élevé, règlement après la construction peut être excessive pour que l'application d'imposer des frais supplémentaires peut-être être appelée pour réduire la compression secondaire. Le principe de l'imposition de frais supplémentaires est simple, mais le comportement de compression secondaire post-surcharge nécessite une étude plus approfondie. Cet article se penche sur les effets de surcharge chargement histoire sur les caractéristiques de compression secondaire post-surcharge des sols. Les connaissances actuelles sur ce sujet repose essentiellement sur le déchargement de stress en supplément à un stress permanent. Il pourrait y avoir d'autres genres d'imposer des frais supplémentaires histoire des contraintes. Par exemple, toutes les précharges, y compris la charge permanente et la charge de la surtaxe, sont supprimés avant que la charge permanente est réappliquée. Données de laboratoire de compression secondaire avec différents histoire surcharge de stress sont présentées et discutées. Ces données fournit des informations utiles pour comprendre le comportement de compression secondaire post-surcharge des sols.

KEYWORDS: Surcharging, precompression, soft soils, secondary compression.

1 INTRODUCTION

Surcharging is a special condition of precompression or preloading technique (e.g. Jamiolkowski et al. 1983, Johnson 1970) for soft ground improvement. The philosophy of surcharging is quite simple that a state of overconsolidation in soil is generated after surcharging executions. It is expected that post-construction settlements of structures are thus reduced. Although, there are some unsuccessful surcharging applications (e.g. Chang 1981, Sower 1964) around the world in which surcharge loads are removed too ealry during primary consolidation so that post-construction settlements resulting from both primary consolidation and secondary compression are still excessive. It is apparent that the philosophy of surcharging is not followed in these cases. To bring the soil to a state of overconsolidation, primary consolidation should have been eliminated completely at the time of surcharge removal. The other situation is that the part of settlement resulting from secondary compression of soil is not usually considered in practice. It should be emphasized that the magnitude of secondary compression settlement may still be significant if conditions allows it to occur. Equation (1) can be used for calculation of secondary compression settlement:

$$s_\alpha = [(C_\alpha / C_c) \times C_c / (1 + e_0)] H_0 \log(t / t_p) \quad (1)$$

Where C_α is the secondary compression index, C_c is the compression index, e_0 is the initial void ratio, H_0 is the initial thickness of soil layer, t_p is the time of end of primary consolidation, and t is any time during secondary compression. A sample calculation can be made with Eq. (1) for a normally consolidated soil layer of 10 *m* thick doubly drained from both top and bottom, with $C_\alpha / C_c = 0.05$, $C_c = 1.0$, e_0 = 1.2, coefficient of consolidation $c_v = 0.001$ cm^2/sec. The time of end of primary consolidation t_p is then estimated as 9 years and the secondary compression settlement at consolidation time of 20 years is calculated using Eq. (1) as 0.08 *m*. If vertical drains were used to speed up primary consolidation, the time of end of priamry consolidation would be greatly shortened. It is assumed for the sample calculation that t_p is reduced to 6 months. Then the secondary compression settlement at consolidation time also of 20 years is calculated again using Eq. (1) as 0.36 *m*. The above sample calculation demonstrates that shortening the time of end of priamry consolidation has an undesirable effect on the magnitude of secondary compression settlement. Secondary compression of natrual soils has been observed both in the field and in the laboratory. As can be seen from Eq. (1), the magnitude of secondary compression settlement is in direct proportion to secondary compression index, thickness of soil layer, and consolidation time considered for calculation. In general, structures on thick soft soils with high natural water contents are highly susceptible to excessive secondary compression settlement. It is easier to estimate secondary compression settlement during design than to face unacceptable post-construction long term settlement problems.

When it is determined during the design stage that seondary compression settlement is excessive or detrimental, surcharging technique can be considered for ground improvement to eliminate part of the undesirable secondary compression settlement. Surcharging application involves using a temporary surcharge load in excess of the permanent load. A question can then be raised as to how much surcharge load is sufficient. Knowledge about relationship between the magnitude of surcharge load and the post-surcharge secondary compression characteristics are required to answer this question. As discussed earlier, the surcharge load should be removed at the end of primary consolidation or without leaving excess pore water in the consolidating soil layer. This renders the soil an overconsolidation state after rebounding with time. The more the surcharge load is removed, the higher the overconsolidation is induced in soil and the longer the time is spent to reach the end of rebound. Furthermore, it has been clearly observed in the laboratory that secondary compression may reappear after the end of rebound. The magnitude of surcharge removal affects both the time of end of rebound and magnitude of post-surcharge secondary compression (Mesri and Feng 1991). Extensive laboratory data of post-surcharge secondary compression of natural soils, including soft clays, silts, and peats, show that the magnitude of post-surcharge secondary compression decreases with increasing the effective surcharge ratio (Mesri and Feng 1991, Mesri et al. 1997, Mesri et al. 2001). When the surcharge load is removed at the end of primary consolidation, the effective surcharge ratio is defined by Eq. (2):

$$R'_s = \left(\sigma'_s - \sigma'_f\right)/\sigma'_f \tag{2}$$

where σ'_s is the effective stress achieved at the end of surcharging and σ'_f is the final effective stress. These data also show that post-surcharge secondary compression always appears when the effective surcharge ratio is less than 1.0, is noticeable for effective surcharge ratios ranging from 0.5 to 1.0, and becomes important for effective surcharge ratios between 0.1 and 0.5. It is the last case in which post-surcharge secondary compression settlement may be excessive. Figure 1 shows consolidation curves obtained from laboratory oedimetric surcharging tests, on a thin-wall tube sample from a lacustrine clay deposit in Taipei, Taiwan, with a final effective stress of 356 kPa and an effective surcharge ratio of 0.23. It is clearly seen from Fig. 1 that secondary compression reappears after surcharge removal and the slope of the post-surcharge secondary compression curve increases gradually up to a maximum value, which is about the same as that of the later portion of the $R'_s = 0$ curve.

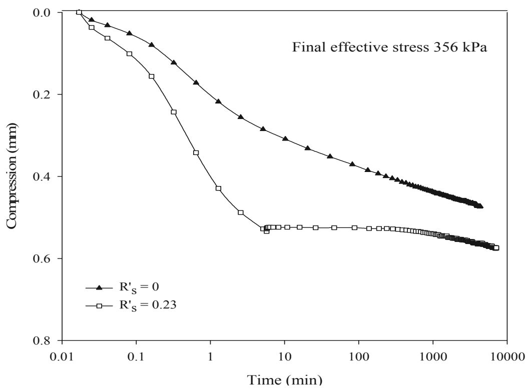

Figure 1. Consolidation curves of Taipei lacustrine clay sample with or without surcharging

In fact, the execution of surcharging from overburden pressure to final effective stress could have a number of different stress histories, as shown in Fig. 2(a)~2(d). Figure 2(a) shows that the consolidation pressure is increased from the overburden pressure to the surcharging stress and then unloaded to the final effective stress. This type of stress history was commonly adopted in most laboratory surcharging tests. Figure 2(b) shows that the consolidation pressure is increased from the overburden pressure to the surcharging stress and then unloaded to the overburden pressure before reloading to the final effective stress. This type of stress history depicts a practical situation in which all preloads, including surcharge load, are removed for the constrcution of permanent sturctures. Figure 2(c) shows that the consolidation pressure is increased from the overburden pressure to the final effective stress without surcharging and then unloaded to the overburden pressure before reloading to the final effective stress. This type of stress history depicts a practical situation in which all preloads, without surcharge load, are removed for the constrcution of permanent sturctures. Figure 2(d) shows that the consolidation pressure is increased from the overburden pressure to the final effective stress without unloading. This type of stress history represents a situation that the permanent structure is constructed without employing precompression technique to reduce secondary compression. It is noted again that these four types of stress histories are different but all ended at the same fianl effective stress. A series of laboratory oedometric surcharging tests with these stress histories are conducted to study the effects, if any, of consolidation stress history on secondary compression. Test results are presented and discussed in this paper.

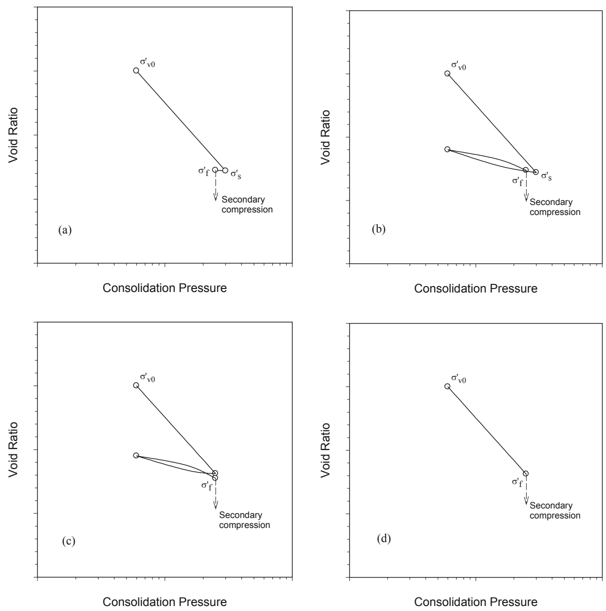

Figure 2. Illustrated surcharging stress histories adopted in this study: (a) unloading from surcharge stress directly to final effective stress, (b) unloading from surcharge stress to overburden pressure before reloading to final effective stress, (c) unloading from final effective stress to overburden pressure before reloading to final effective stress, and (d) without preloading.

2 LABORATORY SURCHARGING TESTS

2.1 *Test program*

The surcharging tests are conducted using conventional oedometer set up with a data acquisition system for taking LVDT (Linear Variable Differential Transformer) readings of specimen compression. The soil tested is a native organic clay sample from Nantou in central Taiwan. The liquid limit and plastic limit of the soil sample are 106% and 44%, respectively. The soil sample is reconstituted in the laboratory with a water content of 155% which is about 1.5 times of the liquid limit. A 200-mm diameter consolidometer is used to prepare identical soil specimens for the surcharging tests. Five oedometer rings are placed with proper spacing in between in the consolidometer and then the consolidometer is filled up with the 155% water content soil sample. The soil in the consolidometer is incrementally loaded to 50 kPa and then unloaded. By this way, five identical oedometer specimens are obtained with a preconsolidation pressure of 50 kPa. These specimens have initial water contents around 88%±1%. Four specimens are used to conduct oedometer tests with different consolidation stress histories illustrated in Figs. 2~5. Specimen #5 is tested according to the stress history described in Fig. 2(a) but is unloaded prior to the end of primary consolidation.

Secondary compression characteristics of natural soils can be expressed in terms of the compressibility ratio C_α/C_c (Terzaghi et al. 1996), where C_α is the secondary compression index and C_c is the compression index. The compressibility ratio and compression index of the organic clay tested are 0.063 and 0.7, respectively. The secondary compression of the laboratory specimens tested with or without surcharging is observed at two different final effective stresses, i.e. 109.6 kPa and 438.4 kPa, for a period that is about two times of the time of end of primary consolidation. Effective surcharge ratios of 0.25 and of 0.125 are used for final effective stresses of 109.6 kPa and of 438.4 kPa, respectively. Significant surcharging test results are presented and discussed herewith.

2.2 *Test results and discussions*

Effect of surcharging on secondary compression, if any, can be directly observed from the consolidation curves with or without surcharging as shown in Fig. 3 and Fig. 4. In these two figures, curve A is the consolidation curve without surcharging, curve B is the consolidation curve with surcharging by the type described in Fig. 2(a), curve C is the consolidation curve with surcharging by the type described in Fig. 2(b), curve D is the consolidation curve with preloading by the type described in Fig. 2(c), and curve E is the consolidation curve with surcharging by the type described in Fig. 2(a) but the specimen is unloaded prior to the end of primary consolidation.

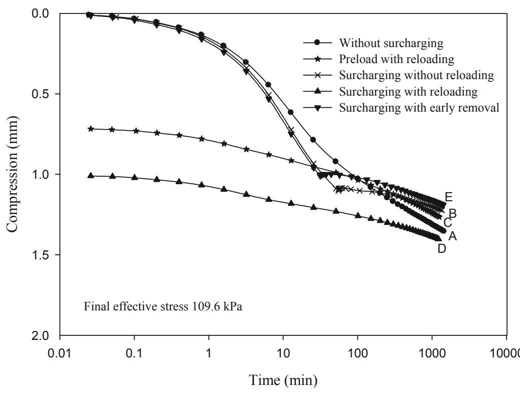

Figure 3. Consolidation curves of different surcharging stress histories with effective surcharge ratio equal to 0.25

It can be seen from Fig. 3 that the slopes of the secondary compression portion of curves B~D are smaller than that of curve A. These data indicate that surcharging or preloading of the types used has reduced the magnitude of secondary compression to somewhat different degrees. Curve E shows about the same magnitude of secondary compression as that of curve A, which can be expected since the specimen is unloaded too early to receive a beneficial effect from surcharging.

Similar test results are shown in Fig. 4 for higher final effective stress and smaller effective surcharge ratio than those shown in Fig. 3. However, it appears from Fig. 4 that the slopes of the later secondary compression portion of all five curves are very close to each other. This is probably partly because the effective surcharge ratio of 0.125 used is rather small so that the reduction in secondary compression is highly limited. These findings suggest that the magnitude of post-surcharge secondary compression is a function of the consolidation stress history imposed on the soft soil. For small effective surcharge ratios achieved in engineering practice, the magnitude of secondary compression may not be reduced to an acceptable level so that long term secondary compression settlement may still be excessive.

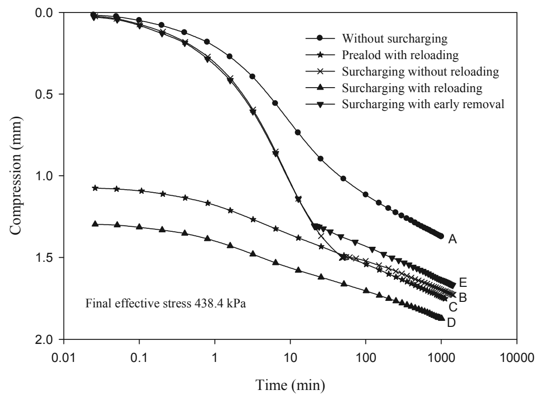

Figure 4. Consolidation curves of different surcharging stress histories with effective surcharge ratio equal to 0.125

The post-surcharge secondary compression characteristics of the Taipei clay are quite different from those of the Nantou clay. Figure 5 shows consolidation curves of these two clays with or without surcharging, all in the normally consolidated range. The load increment ratio used for the increments without surcharging is 1. The loading increment ratio used for the increments with surcharging is higher than 1 since the surcharge load is added with the final load at the same time. The surcharge load is removed at a time near the end of primary consolidation. During the primary consolidation stage, the Nantou clay specimen consolidates much slower and compresses more than those of the Taipei clay specimen. The compressibility ratio and compression index of the Taipei clay are 0.039 and 0.3, respectively, which are much smaller than those of the Nantou clay. It can be seen from Fig. 5 that, after surcharge removal, the Taipei clay specimen rebounds slightly and continuously for a relatively long period of time before secondary compression appears. As a comparison, the Nantou clay specimen rebounds very slightly and shortly before secondary compression appears. The effective surcharge ratios used in these tests are about the same and do reduce the secondary compression to a certain degree. But it appears that characteristics of post-surcharge secondary compression vary from one soil to another soil.

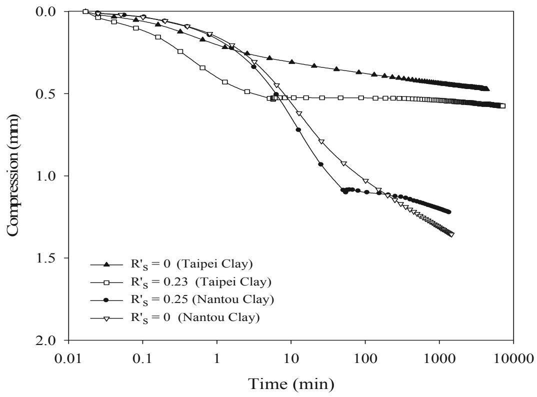

Figure 5. Consolidation curves of different soils with or without surcharging

3 CONCLUSIONS

The following conclusions are based on data and discussions presented in previous paragraphs. Surcharging with higher effective surcharge ratio reduces secondary compression to a lower magnitude. For the same effective surcharge ratio, surcharging without reloading reduces more secondary compression than surcharging with reloading. The post-surcharge secondary compression is also a function of the surcharging stress history achieved in the consolidating soil. For small effective surcharge ratios realized in practice, the secondary compression of soil may not be reduced sufficiently and excessive long term settlement resulting from secondary compression may still be expected. Structures on natural thick soil deposit with high compressibility ratio, e.g. greater than 0.04, and improved by prefabricated vertical drains are highly susceptible to excessive long term secondary settlement. In this case, surcharging technique is capable of reducing the secondary settlement, as long as a proper value of effective surcharge ratio is used in design and achieved in soil.

4 ACKNOWLEDGEMENTS

This study is partly supported by the National Science Council of Taiwan, under Grant No. NSC 98-2221-E-033-052-MY2, and by Chung Yuan Christian University. Great thanks are given to these organizations for their continuous support.

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