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Vacuum distribution with depth in vertical drains and soil during preloading

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Abstract. The vacuum consolidation method which was proposed by Kjellman in 1952 has been studied extensively and used successfully since early 1980 throughout the world, especially in East and Southeast Asia. Despite the increased successful use, different opinions still exist, especially in connection to distribution of vacuum with depth and time in vertical drains and in soil during preloading of soft ground. Porewater pressure measurements from actual cases of field vacuum and vacuum-fill preloading as well as laboratory studies have been examined. It is concluded that (a) a vacuum magnitude equal to that in the drainage blanket remains constant with depth and time within the vertical drains, (b) as expected, vacuum does not develop at the same rate within the soil at different depths; however, under ideal conditions vacuum is expected to become constant with depth in soil after the end of primary consolidation, and (c) there exists a possibility of internal leakage in vacuum intensity at some sublayers of a soft clay and silt deposit. A case history of vacuum loading with sufficient subsurface information is analyzed using the ILLICON procedure.

Keywords: vacuum consolidation; vacuum pressure distribution; preloading; ground improvement

1. Introduction

Improvement of soft ground using vacuum as a preload was first suggested by Kjellman in 1952. Since then, the vacuum together with vertical drains method has been extensively studied and successfully used in different parts of the world. Despite increasing use of the method, different opinions exist on the transmission of vacuum to the ground as well as on vacuum consolidation and increase in shear strength (Mesri and Khan 2011, 2012).

The assumption on distribution of vacuum with depth within vertical drains is a significant factor that has a direct influence on design of preloading as well as on the back-analysis of field observations of settlement and porewater pressure. Assuming a vacuum intensity within vertical drains constant with depth justifies analysis of vacuum loading similar to a wide fill loading, whereas, for example, assuming a linear decrease in vacuum with depth in vertical drains (Indraratna *et al*. 2004, 2005, Chai *et al*. 2005a, b and 2009) suggests a limit on the depth of ground improvement using vacuum preloading. Although there are only limited data on measurement of vacuum within vertical drains (Shang *et al*. 1998, Berthier *et al*. 2009), a limiting

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depth of ground improvement is not supported by field evidence and more importantly, it has not been proposed as a general approach to vacuum preloading (Mesri and Khan 2011, 2012).

Porewater pressure measurements with depth in soil provide an indirect evidence on distribution with depth of vacuum within vertical drains. Porewater pressure data from laboratory studies and field case histories were reviewed and analyzed to ascertain vacuum distribution with depth (Khan 2010). These data are briefly reviewed here, and the importance of the assumption on vacuum distribution in vertical drains with depth and time is highlighted by the analyses of a case history of vacuum preloading.

2. Laboratory studies of vacuum preloading

Laboratory studies of vacuum preloading have been reviewed and interpreted in detail by Khan (2010). The laboratory study by Rujiakiatkamjorn (2005) which proposed a linear decrease in vacuum with depth in vertical drains (also proposed by Bamunawita 2004) is examined and reinterpreted here. Rujiakiatkamjorn (2005) carried out a series of one-dimensional compression tests in a 450 mm diameter and 900 mm high Teflon-lined confining cylinder. The reconstituted clay specimens were provided with a prefabricated vertical drain (PVD) at the center. Five tests were conducted under the following loading conditions: vertical load of 30 kPa (SP1), vacuum load of 20 kPa (VP1), vacuum load of 40 kPa (VP2), vertical load of 30 kPa and vacuum load of 20 kPa (SV1), and vertical load of 30 kPa and vacuum load of 40 kPa (SV2). The vertical load and vacuum were applied to the top of the specimen which served as the drainage boundary. Porewater pressure distribution was measured using six transducers place in soil at vertical distances of 110 mm, 430 mm, and 750 mm from the top of the specimen, at radial distances of 70 mm and 140 mm.

Assuming a homogeneous reconstituted soil over the 640 mm length, the porewater pressure measurement, shown in Figs. 1 and 2, suggest that: (a) a uniform increase with depth in effective vertical stress is produced by a decrease in porewater pressure associated with either fill loading, or vacuum loading through vertical drains; (b) porewater pressure change associated with a wide fill load or vacuum load applied through vertical drains, is uniform with depth; however, because of the contribution of vertical water flow through soil into the drainage boundary at the top, rate of porewater pressure change is somewhat higher near the top and somewhat lower near the impermeable boundary at the bottom; and (c) the uniform distribution of porewater pressure with depth within the soil provides an indirect evidence of uniform distribution of vacuum with depth within vertical drains.

3. Field studies of vacuum preloading

The observed decreases in porewater pressure in soil are shown in Figs. 3, 4, and 5 for three case histories of vacuum preloading. As is expected, in natural soil profiles in which compressibility and permeability may change with depth, vacuum does not develop at the same rate within the soil at different depths even though vacuum is constant with depth in the vertical drains. In Fig. 3, consolidation progressed rapidly in the depth range of 6 to 11 m, whereas the rate of porewater pressure change was slowest near the depths of 4 and 14.5 m. After 90 days, the porewater pressures at all depth, except at 4 and 14.5 m, were approaching the vacuum in the

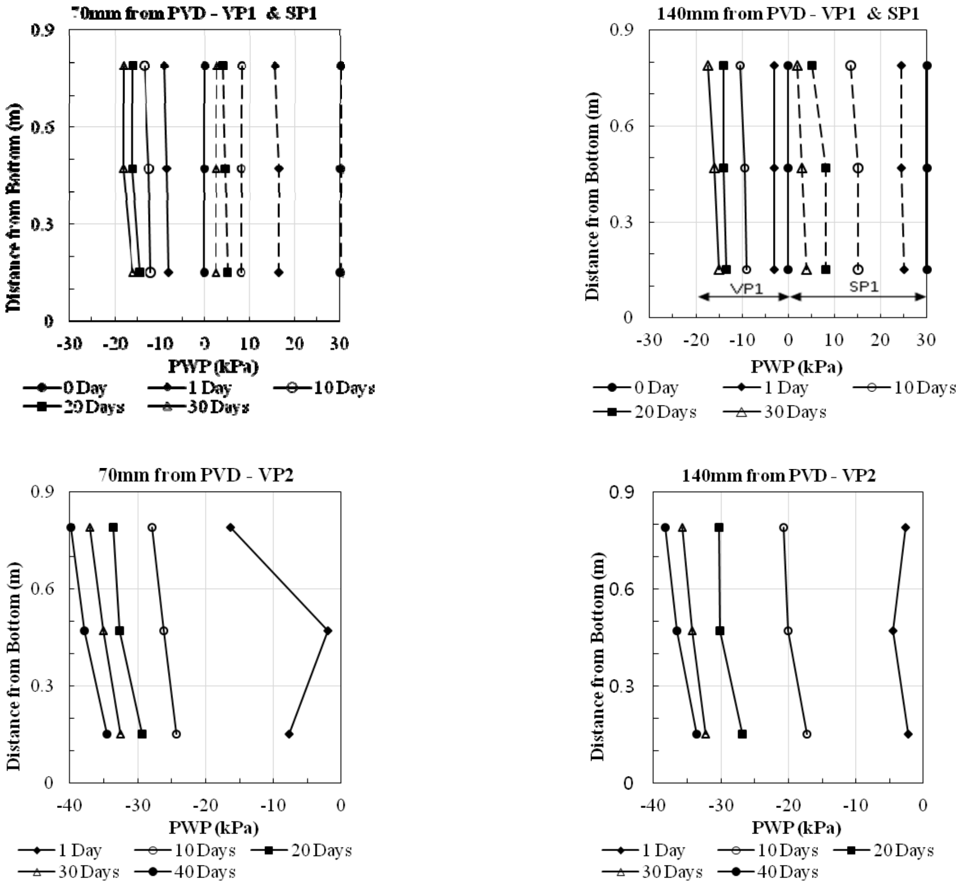


Fig. 1 Porewater pressure distribution with depth and time in soil at two radial distances from PVD for vacuum and fill preloads (Data from Rujiakiatkamjorn 2005)

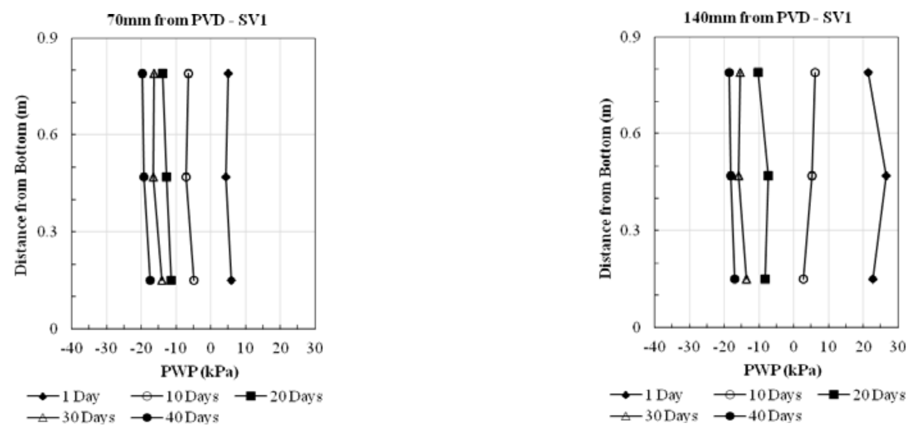


Fig. 2 Porewater pressure distribution with depth and time in soil at two radial distances from PVD for vacuum plus fill preloads (Data from Rujiakiatkamjorn 2005)

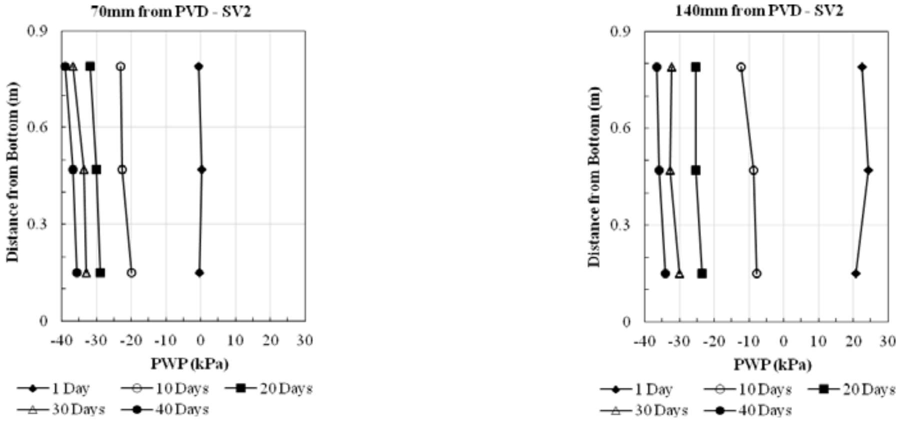


Fig. 2 Continued

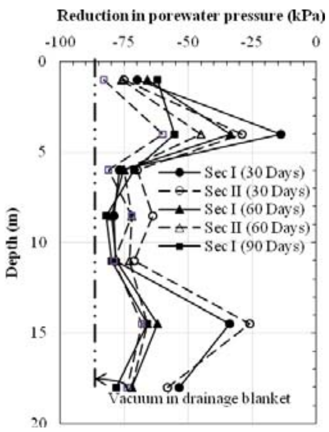


Fig. 3 Observed distribution of vacuum with depth and time in soil (Data from Yan and Chu 2003)

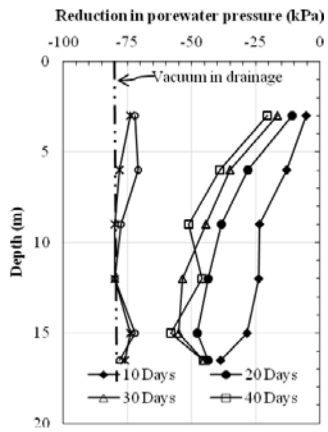


Fig. 4 Observed distribution of vacuum with depth and time in soil (Data from Yan and Chu 2005)

drainage blanket suggesting a uniform distribution of vacuum with depth within the vertical drains.

The porewater pressure measurements in Fig. 4 suggest that consolidation was progressing faster near the bottom of the soil deposit than near the top. However, after 180 days, in the depth range of 3 to 16.5 m, vacuum in soil had approached the vacuum in the drainage blanket, and was almost constant with depth, suggesting uniform distribution of vacuum with depth within the vertical drains.

The porewater pressure measurements in Fig. 5 show that within a vertical drain length of 15 m, vacuum remained more or less constant with depth, near 80 kPa, in an elapsed time of 28 to 184 days, again supporting uniform distribution of vacuum with depth within vertical drains.

Under ideal conditions vacuum is expected to become constant with depth in soil after the end of primary consolidation. However, as is illustrated by the case history described in the next

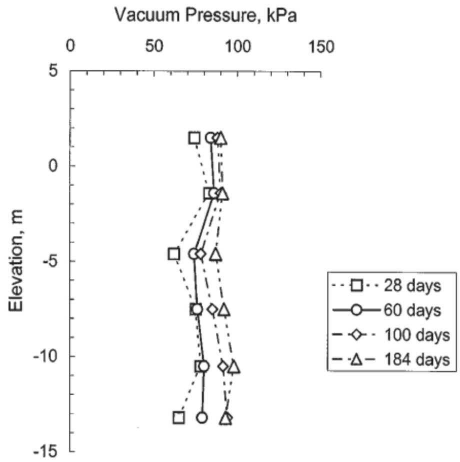


Fig. 5 Observed distribution of vacuum with depth and time in vertical drains (after Shang *et al.* 1998)

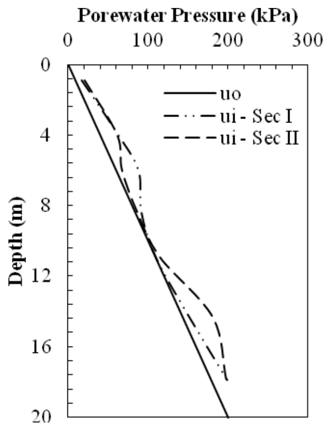


Fig. 6 Pre-treatment excess porewater pressures in Section I and Section II

section there may be internal leakage in that vacuum in soil sublayers may not reach the vacuum available within the vertical drains.

4. Improvement of soft ground using vacuum preloading – A case study

Vacuum preloading was used to improve soft ground to construct a road leading to container terminal in China. The 20 m thick compressible ground is divided into a top 6 m dredged silty clay over the 14 m thick seabed clay deposit. Before the commencement of precompression, the dredged clay and seabed clay were undergoing primary consolidation as evidenced by porewater pressure measurements in Fig. 6. The position of ground water table was not reported; however,

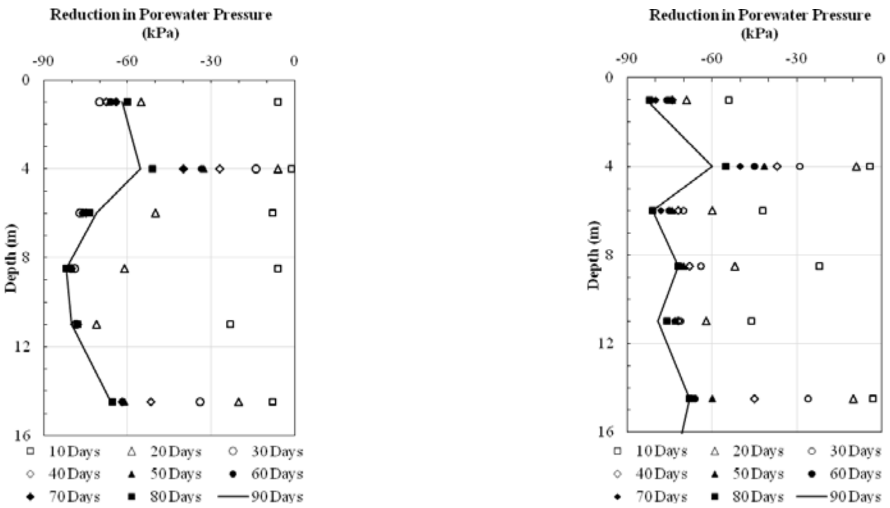


Fig. 7 Observed distribution of vacuum with depth and time in soil in Section I and Section II (data from Yan and Chu 2003)

porewater pressure data in Yan and Chu (2003) suggest groundwater table at the ground surface. For settlement analysis, the 20 m soft ground was divided into 7 sublayers; a 2 m thick stiff clay was also included in the settlement analyses to account for the settlement occurring below the PVD penetration depth of 20 m. Based on actual porewater pressure data reported by Yan and Chu (2003) a final vacuum distribution of 80 kPa at the top and zero at the bottom of the 2 m thick stiff clay was assumed. The bottom of the stiff clay was treated as an impermeable boundary.

The ground surface was covered with a 0.3 m thick sand blanket through which prefabricated vertical drains were installed in a square grid of 1 m spacing, to a depth of 20 m. Corrugated flexible pipes with a diameter of 100 mm, wrapped in a filter fabric, were placed inside the sand blanket to link PVDs to vacuum source. Three layers of PVC membranes were used to seal the drainage blanket, and then vacuum was applied using jet pumps (Yan and Chu 2005). During a period of 42 days between placement of sand blanket, installation of vertical drains and first application of vacuum, a ground surface settlement of 0.58 m took place under the load of the sand blanket and equipment movement as well as dissipation of pretreatment excess porewater pressures. Fig. 7 shows observed decreases in porewater pressure at maximum horizontal distance from vertical drains, as a function of depth and time.

The procedure for settlement analysis for vacuum loading using the ILLICON has been described in detail in Mesri and Khan (2012); however, key features of ILLICON (a settlement analysis program developed at University of Illinois at Urbana Champaign, USA by Prof Mesri and his coworkers) are:

- The program can handle up to 15 layers, each having its own distinct properties including initial void ratio, initial effective vertical stress, preconsolidation pressure, e – logσ'_v and e – logk_v relations, and secondary compression index.
- Time-dependent increase and decrease in load to simulate actual loading schedule in the field can be modeled. Additionally, the program can accommodate any assumption on

distribution (including elastic stress distribution) of applied load with depth and with time. This is a very significant feature as it allows to account for any leakage or stoppage in applied vacuum and its subsequent reapplication after a certain period of time.

- The program can handle fully as well as partially penetrating vertical drains and accounts for flow in both vertical and horizontal direction within the soil when vertical drains are used. This is useful as the vertical drains used together with vacuum preloading are terminated short of the bottom drainage boundary (assuming the vacuum to be applied from the top).

For the case history of vacuum loading described here the 0.3 m thick drainage blanket was considered as a 6 kPa uniform strip load over the ground surface, the pretreatment excess porewater pressures at any depth were considered to result from a vertical stress increase at the beginning of ground treatment, and a temporary construction equipment load of 10 kPa was assumed over a period of 2 weeks. The details of settlement analyses using the ILLICON, including input data on compressibility and permeability of the sublayers, and assumptions on smear zone around vertical drains and well resistance, are reported in Khan (2010).

Based on the observed porewater pressure profiles, the following assumptions on vacuum distribution with depth were evaluated in terms of the observed surface and subsurface settlements:

4.1 For Section I

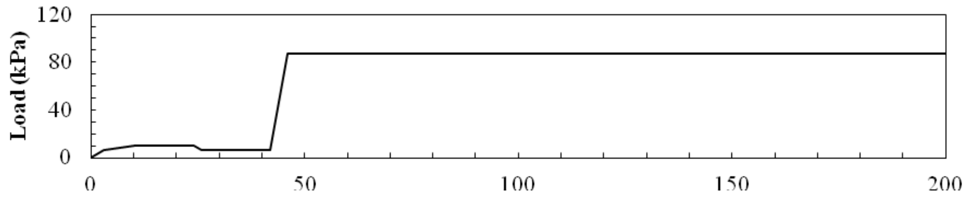
- Assumption A, vacuum of 87 kPa developed uniformly with depth in the vertical drains and at the end of primary consolidation in the soil (Fig. 8(a)).
- Assumption B, vacuum of 80 kPa developed uniformly with depth in the vertical drains; however, the vacuum in vertical drains and at the end of primary consolidation in the soil stabilized at 60 kPa (Fig. 8(b)).
- Assumption C, different segments of vertical drains within sublayers were subjected to different vacuum; therefore end of primary vacuum was different for the sublayers (Fig. 8(c)).

4.2 For Section II

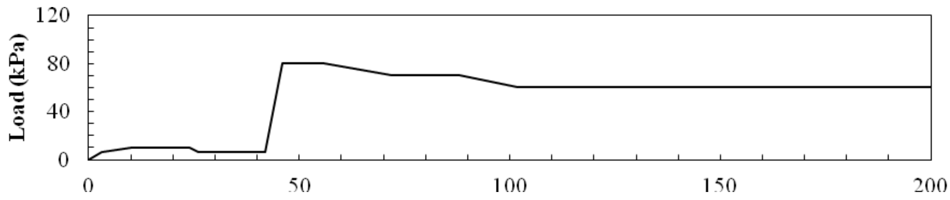
- Assumption D, vacuum of 70 kPa developed uniformly with depth within the vertical drains; however, the vacuum later increased to a uniform 87 kPa with depth in the vertical drains (Fig. 11(a)).

4.3 Observed and predicted settlements

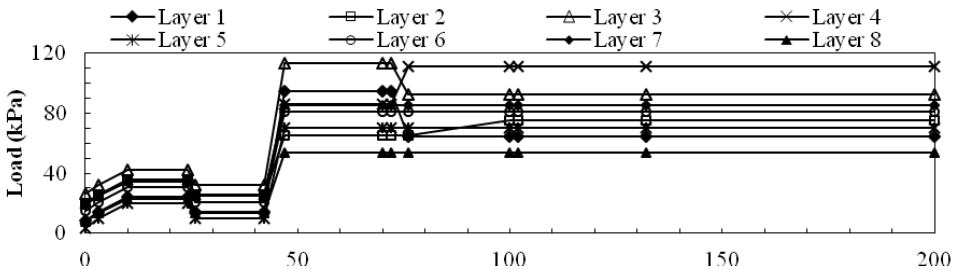
The predicted surface settlements based on three different assumptions on vacuum magnitudes and distribution within the vertical drains are compared with observations in Fig. 8(d). Because settlement observations began at the application of vacuum 42 days after placement of drainage blanket, a surface settlement of 0.58 m was added for comparison of total computed and observed settlements. A computed subsurface settlement was similarly added to the observed subsurface settlements. Fig. 8(d) shows that loading Assumption A somewhat overpredicted the settlements, whereas Assumptions B and C lead to settlements in reasonable agreement with observations. Surface and subsurface settlements predicted using Assumptions B and C are compared with



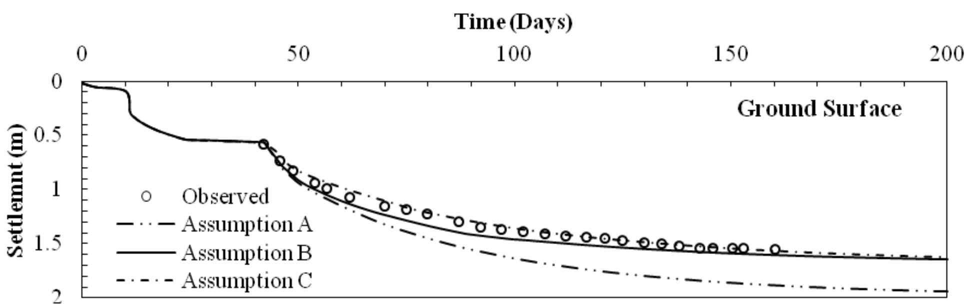
(a) Assumption A: Uniform vacuum intensity in drainage layer and all along the depth of PVDs



(b) Assumption B: Vacuum quickly reached to 80kPa and then gradually decreased to 60kPa



(c) Assumption C: Vacuum developed in different sub-layers independent of each other



(d) Settlement resulting from different assumptions

Fig. 8 Different assumptions on vacuum distribution in vertical drains and resulting settlements for Section I

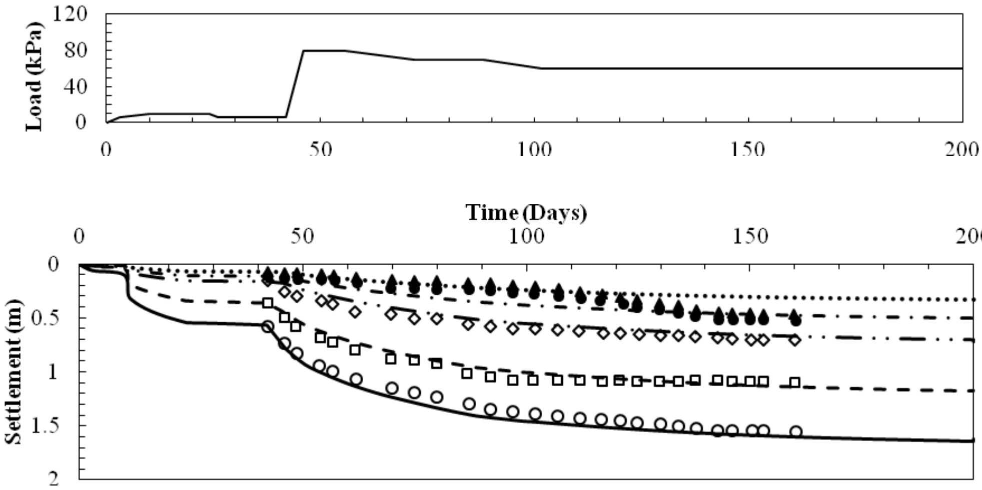


Fig. 9 Predicted surface and subsurface settlements for Assumption B compared with observed settlements, for Section I (Observed data from Yan and Chu 2003)

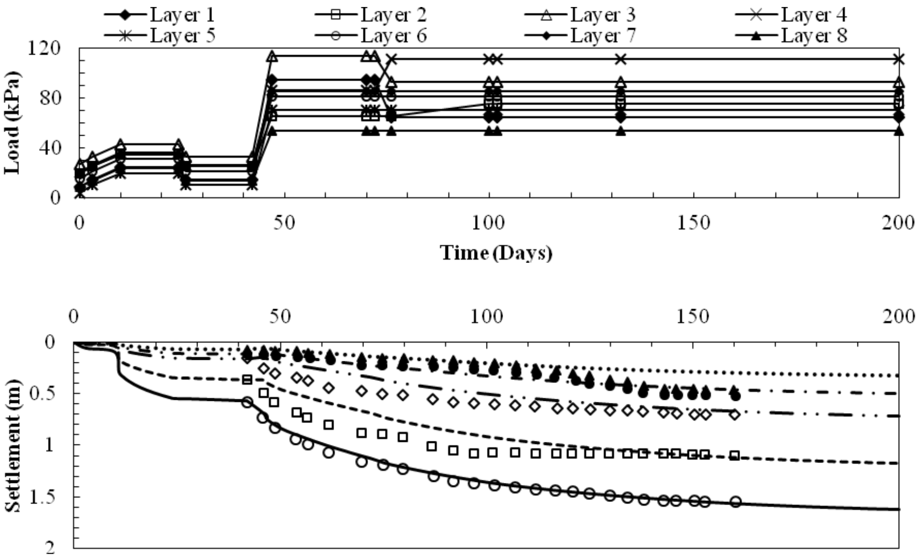
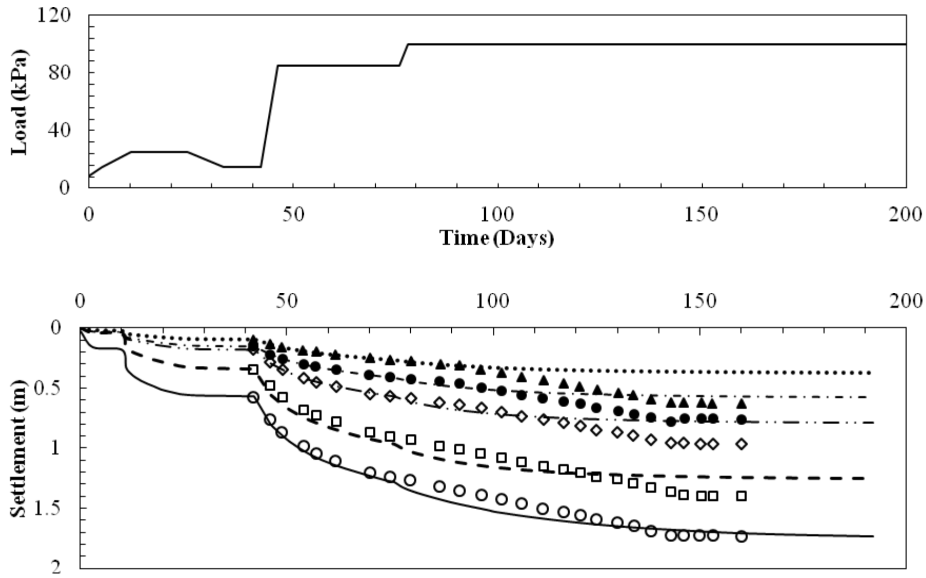


Fig. 10 Predicted surface and subsurface settlements for Assumption C compared with observed settlements, for Section I (Observed data from Yan and Chu 2003)

observations, respectively, in Figs. 9 and 10. Assumption B leads to a fair and Assumption C to a good agreement between predicted and observed subsurface settlements.

For Section II, Assumption D leads to predicted surface and subsurface settlements in Fig. 11 that are in fair agreement with observations.



Depth (m)	Surface	2	5.5	9.5	13
Observed	○	□	◇	●	▲
ILLICON	———	- - - - - - -	—··—··—	-·-·-·-·-	············

Fig. 11 Predicted surface and subsurface settlements for Assumption D compared with observed settlements, for Section II (Observed data from Yan and Chu 2003)

The comparisons of surface and subsurface settlements predicted by ILLICON analyses to observed settlements, in Figs. 8, 9, 10, and 11, suggest that: (1) it is possible for vacuum to reach different maximum values in different soil sublayers; (2) vacuum may initially develop to a high value, but then with time stabilize at a lower value; and (3) because of internal horizontal leakage in some sublayers, vacuum in soil may not reach the vacuum magnitude available in the drainage blanket and vertical drains.

4.4 Observed and predicted porewater pressures

Mesri and Khan (2012) proposed the following equation for interpreting porewater pressure during vacuum or vacuum plus fill loading

$$u = u_o + u_{sm} + u''$$

where u is total porewater pressure, u_o is the initial preconstruction ground water pressure, u_{sm} is the applied maximum vacuum (negative porewater pressure), and u'' is a positive excess porewater pressure from ILLICON analysis with possible maximum value of $|u_{sm}| + \Delta\sigma_v$, where $\Delta\sigma_v$ is increase in total vertical stress by fill loading.

The predicted total porewater pressures for assumptions B, C, and D are compared with

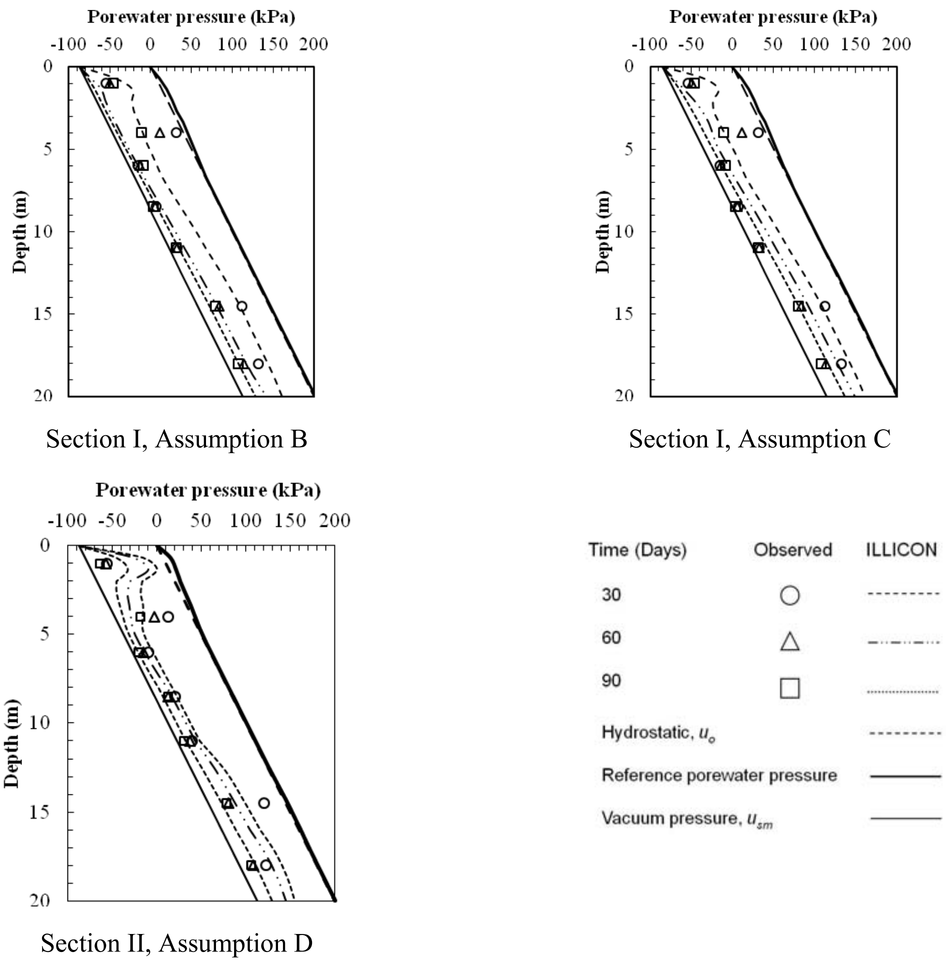


Fig. 12 Observed and predicted porewater pressure distribution with depth and time (Observed data from Yan and Chu 2003)

observed values in Fig. 12. As in the case of the observed settlement data, porewater pressures reported by Yan and Chu (2003) have been adjusted by using the predicted porewater pressures at 42 days after placement of the drainage blanket. For assumptions B, C, and D, there is good agreement between predicted and observed porewater pressures.

Based on the ILLICON analyses of consolidation, degree of primary consolidation for the 20 m thick soil layer at the end of the vacuum preloading operation, at Section I was 80 to 86%, and at Section II it was 87%.

5. Conclusions

The following conclusions are based on analyses and interpretation of laboratory test data and field preloading using vacuum together with vertical drains:

- There is no reliable laboratory or field evidence to suggest that vacuum in vertical drains decreases systematically with depth. In fact, for design of preloading using vacuum together with vertical drains, vacuum in vertical drains can be assumed equal to the value available in the drainage blanket and to be constant with depth.
- As is expected, vacuum does not develop at the same rate within a soil profile with compressibility and permeability that may vary with depth, and because of the contribution of water flow within soil in vertical direction toward the drainage blanket.
- In highly stratified deposits because of the possibility of internal leakage, vacuum in some soil layers may not reach the maximum value available within the drainage blanket and vertical drains.
- Because of the possibility of internal leakage, a refined settlement analyses, including predicting the increase in undrained shear strength, for precompression using vacuum together with vertical drains, may rely on the observational method of measuring porewater pressures in vertical drains and within soil and adjusting the predictions.

References

Bamunawita, C. (2004), “Soft clay foundation improvement via prefabricated vertical drains and vacuum preloading”, Ph.D. Thesis, University of Wollongong, Australia.

Berthier, D., Boyle, P., Ameratunga, J., Bok, C.D. and Vincent, P. (2009), “A successful trial of vacuum consolidation at the port of Brisbane”, *Coasts and Ports Conference*: *In a Dynamic Environment*, Wellington, New Zealand, March, pp. 640-647.

Chai, J.C., Carter, J.P. and Hayashi, S. (2005a), “Ground deformation induced by vacuum consolidation”, *J. Geotech. Geoenviron. Eng*., *ASCE*, 1552-1561.

Chai, J.C., Hayashi, S. and Carter, J.P. (2005b), “Characteristics of vacuum consolidation”, *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering*, International Society for Soil Mechanics and Geotechnical Engineering and the Japanese Geotechnical Society, Osaka, Japan, pp. 1167-1170.

Chai, J.C., Matsunaga, K., Sakai, A. and Hayashi, S. (2009), “Comparison of vacuum consolidation with surcharge load induced consolidation of a two-layer system”, *Géotechnique*, **59**(7), 637-641.

Chu, J. and Yan, S.W. (2005). “Estimation of degree of consolidation for vacuum preloading projects”, *Int. J. Geomech*., *ASCE*, 158-165.

Chu, J., Yan, S.W. and Zheng, Y.R. (2006), “Three soil improvement methods and their application to road construction”, *Ground Improv*., **10**(3), 103-112.

Indraratna, B., Bamunawita, C. and Khakbaz, H. (2004), “Numerical modeling of vacuum preloading and field applications”, *Can. Geotech. J.*, **41**(5), 1098-1110.

Indraratna, B., Sathananthan, I., Bamunawita, C. and Balasubramanium, A.S. (2005), “Theoretical and numerical perspectives of field observations for the design and performance evaluation of embankment constructed on soft marine clay”, University of Wollongong, Australia.

Kjellman, W. (1952), “Consolidation of clay soil by means of atmospheric pressure”, *Proceedings of the Conference on Soil Stabilization*, MIT, Cambridge, MA, USA, June, pp. 258-263.

Khan, A.Q. (2010), “Ground improvement using vacuum preloading together with prefabricated vertical drains”, Ph.D. Thesis, University of Illinois at Urbana-Champaign, Urbana, IL, USA.

Mesri, G. and Khan, A.Q. (2010), “Interpretation of vacuum preloading using ILLICON methodology”, *International Conference on Geotechnical Engeeneering*, Lahore, Pakistan, November, pp. 27-36.

Mesri, G. and Khan, A.Q. (2011), “Increase in shear strength due to vacuum preloading”, *Proceedings of the 2011 Pan-Am CGS Geotech Conference*, Toronto, Canada, January.

Mesri, G. and Khan, A.Q. (2012), “Ground improvement using vacuum loading together with vertical

drains", *J. Geotech. Geoenviron. Eng.*, *ASCE*, **138**(6), 1-10.
Rujikiatkamjorn, C. (2005), "Analytical and numerical modeling of soft clay foundation improvement via prefabricated vertical drains and vacuum preloading", Ph.D. Thesis, University of Wollongong, Australia.
Shang J.Q., Tang, M. and Miao, Z. (1998), "Vacuum preloading consolidation of reclaimed land: A case study", *Can. Geotech. J.*, **35**(5), 740-749.
Yan, S.W. and Chu, J. (2003), "Soil improvement for a road using the vacuum preloading method", *Ground Improv.*, **7**(4), 165-172.
Yan, S.W. and Chu, J. (2005). "Soil improvement for a storage yard using the combined vacuum and fill preloading method", *Can. Geotech. J.*, **42**(4), 1094-1104.

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