Increase in Shear Strength Due to Vacuum Preloading

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ABSTRACT

The use of vacuum together with vertical drains, as a preload, to reduce post construction settlements and to improve shear strength of soft soils, is becoming increasingly popular around the world. Unfortunately, conflicting views have been published concerning undrained shear strength increase resulting from vacuum preloading. It is demonstrated in this paper that the empirical concepts concerning undrained shear strength of soft clay and silt deposits that have been developed based on fill loading are equally applicable to vacuum loading. For soft clay and silt deposits subjected to a constant increase in effective vertical stress with depth, resulting from either vacuum loading or fill loading, s_u/s_{uo} decreases with depth, $(s_u – s_{uo})$ remains constant with depth for soil profiles with either $\sigma'_p/\sigma'_{vo} = 1$ or $(\sigma'_p - \sigma'_{vo})$ = constant with depth, and $(s_u – s_{uo})$ decreases with depth for soil profiles with σ'_p/σ'_{vo} greater than one. With subsurface information on the vertical profiles of σ'_p/σ'_{vo}, s_{uo}/σ'_p, and $\Delta\sigma'_v$ resulting from vacuum, vacuum plus fill or fill loading, vertical profile of $(s_u – s_{uo})$ can be predicted.

RÉSUMÉ

L'application du vide comme système de préchargement et l'utilisation de drains verticaux pour réduire les tassements après construction et augmenter la résistance au cisaillement du sol, est de plus en plus populaire à travers le monde. Malheureusement des opinions contradictoires se retrouvent dans la littérature en ce qui concerne l'augmentation de la résistance au cisaillement non drainé suite à un préchargement par l'application du vide. L'objectif de cet article est de montrer que les approches empiriques développées pour évaluer l'augmentation de la résistance au cisaillement non drainé des dépôts d'argile molle ou de silt lors de surcharge par remblai sont également applicables lorsque la surcharge résulte de l'application du vide. Pour des dépôts d'argile molle ou de silt soumis à une augmentation de contrainte effective constante avec la profondeur due à un chargement appliqué par le vide ou par un remblai, S_u/S_{uo} diminue avec la profondeur, $(S_u - S_{uo})$ est constant avec la profondeur pour des profils de sol avec, soit $\sigma'_p/\sigma'_{vo} = 1$ ou (σ'_p/σ'_{vo}) = constant avec la profondeur, et $(S_u - S_{uo})$ diminue avec la profondeur pour des profils de sol avec σ'_p/σ'_{vo} = plus grand que l'unité. Avec des informations sur les profils de σ'_p/σ'_{vo}, de S_{uo}/σ'_p et de $\Delta\sigma'_v$ résultant d'un préchargement par application du vide, par un remblai ou par un remblai en plus de l'application du vide, les profils de $(S_u - S_{uo})$ peuvent être prédits.

1 INTRODUCTION

One distinct advantage of preloading using vacuum as compared to preloading by fill is the increase in undrained shear strength of soft ground without the possibility of undrained bearing capacity failure during preloading operation. For this reason, vacuum load can be applied to the surface drainage blanket and vertical drains as rapidly as the vacuum pumping system and compliance of connections allow, whereas in most of cases, fill preload, which applies shear stresses near the boundaries of the preloaded area, must be placed in stages to avoid excessive undrained deformation and failure.

Unfortunately, conflicting views have been published concerning: (a) undrained shear strength increase resulting from vacuum preloading as compared to undrained shear strength increase resulting from fill preloading, and (b) behavior of undrained shear strength increase resulting from vacuum preloading as a function of depth below ground surface. In this paper existing data on undrained shear strength increase in soft clay and silt deposits resulting from vacuum loading are reviewed and compared with undrained shear strength increase resulting from equivalent fill loading, concluding that, for all practical purposes, there is no difference in undrained shear strength behavior connected to vacuum or fill loading. Therefore, existing empirical knowledge on undrained shear strength of soft clay and silt deposits that has resulted from application of total stress by fill load, consolidation and associated increase in effective stress, can be used to predict undrained shear strength resulting from application of vacuum, consolidation and associated increase in effective stress.

2 PRECOMPRESSION BY VACUUM VERSUS FILL PRELOADING

Based on experience with undrained shear strength of soft clay and silt deposits subjected to fill loading, expressions have been developed for undrained shear strength as a function of consolidation pressure (Ladd et al. 1977, Terzaghi et al. 1996). During the increase in effective vertical stress and primary consolidation in the compression range, i.e. σ'_v greater than σ'_p

$$s_u = \frac{s_{uo}}{\sigma'_p}\sigma'_v \qquad [1a]$$

and during the decrease in effective stress and primary rebound from a σ'_{vm} greater than σ'_p

$$s_u = \frac{s_{uo}}{\sigma'_p}\left(\frac{\sigma'_{vm}}{\sigma'_v}\right)^m \sigma'_v \qquad [1b]$$

where s_{uo} is initial undrained shear strength, σ'_p is preconsolidation pressure, $\sigma'_v = (\sigma'_{vo} + \Delta\sigma'_v)$ is effective vertical stress during primary consolidation or primary rebound, σ'_{vo} is initial effective vertical stress, $\Delta\sigma'_v$ is the increase in effective vertical stress measured from the initial condition, σ'_{vm} is effective vertical stress from which unloading takes place, and m is the slope of linear relationship between $\log(s_u/\sigma'_v)$ versus $\log(\sigma'_{vm}/\sigma'_v)$, with intercept s_{uo}/σ'_p.

Applied to preloading using vacuum, when σ'_v is greater than σ'_p

$$s_u = \frac{s_{uo}}{\sigma'_p}\sigma'_v \qquad [2a]$$

where $\sigma'_v = (\sigma'_{vo} + p_v)$, and p_v is vacuum in soil during consolidation and is equal or greater than $(\sigma'_p - \sigma'_{vo})$, and

$$s_u = \frac{s_{uo}}{\sigma'_p}\left(\frac{\sigma'_{vs}}{\sigma'_v}\right)^m \sigma'_v \qquad [2b]$$

where $\sigma'_{vs} = (\sigma'_{vo} + p_{vs})$, and p_{vs} is vacuum in soil when it is turned off, which may range from p_v to imposed vacuum available in the drainage system.

As an example, a soil with σ'_{vo} =40kPa, $\sigma'_p/\sigma'_{vo} = 1.4$, $s_{uo}/\sigma'_p = 0.25$, and m = 0.8 is subjected to 80kPa vacuum in the drainage system. During consolidation when vacuum in the soil is 60kPa, $\sigma'_v = (\sigma'_{vo} + p_v)$ =100kPa and using Eq. 2a, s_u = 25kPa. If vacuum is maintained until p_v = 80kPa in soil, then σ'_v = 120kPa and s_u = 30kPa.

If vacuum is turned off when p_{vs} = 60kPa in soil, then when p_v = 30kPa in soil, from Eq. 2b, s_u = 23kPa, and when p_v = 0 in soil, s_u = 21kPa.

If vacuum is turned off when p_{vs} = 80kPa in soil, then when p_v = 30kPa in soil, s_u = 27kPa, and when p_v = 0 in soil, s_u = 24kPa.

Qian et al. (1992) used Eq. 2b in an unrecognizable form, together with σ'_p/σ'_{vo} =1 and m=0.8, to compute the increase in undrained shear strength of subsoil at a factory site by the seashore in Lianyungang City, China. The 10m thick marine clay with initial undrained shear strength of 5.7 to 19.6kPa was treated with 10m long and 70mm diameter vertical drains spaced at 1.2m, and subjected to p_{vs} = 87kPa. Qian et al. (1992) reported nearly perfect agreement between the calculated and measured undrained shear strength increase. Because Eq. 2b was based on observed undrained shear strength behavior of soft clay and silt deposits subjected to fill loading, field experience reported by Qian et al. (1992) suggests that a similar increase in undrained shear strength is produced by vacuum loading and fill loading.

Equation 2b was also adopted by Chai et al. (2008) for computing undrained shear strength increase resulting from vacuum consolidation, reporting reasonably good agreement with measurements.

Choa (1989, 1990), Yixiong (1996a, b) and Shang et al. (1998) report a detailed study of land reclamation at the East Pier of Xingang Port in Tianjin, China. The soft ground of 17 to 20m thickness consisted of layers of organic silt and clay with lenses of silty fine sand, and peat, including a 4m thick very soft newly reclaimed surface layer of underconsolidated dredged silty clay/ clayey silt. Natural water content, liquid limit, and field vane undrained shear strength were, respectively, in the range of 44 to 64%, 35 to 53%, and 5 to 30kPa. In three control subdivisions prefabricated vertical drains with spacing of 1.3m were installed to a depth of 16 to 20m, and were subjected to vacuum load of 80 to 90kPa (subdivision 12 – 13), vacuum load of 80 to 90kPa plus fill load of 17kPa (subdivision 44), and fill load of 97kPa (subdivision S-2). The average treatment time ranged from 135 to 175 days.

The settlement observations and field vane shear tests led Shang et al. (1998) to conclude that vacuum preloading and fill preloading generated similar consolidation effects. Significant undrained shear strength increases of 20 to 27kPa were measured over entire treatment depth.

For two field pilot tests at Yaoqiang Airport near Jinan, China, Tang and Shang (2000) reported “similar results”, including for settlement and increase in field vane undrained shear strength, for a subsoil consisting of layers of clayey silt, silty clay and soft clay, treated to a depth of 12m with prefabricated vertical drains with spacing of 1.3m, and subjected to a 80kPa preload by either vacuum loading or fill loading.

In order to compare the increase in undrained shear strength resulting from vacuum preloading and fill preloading, Leong et al. (2000) subjected undisturbed specimens of Kallang marine clay formation of Singapore to either oedometer compression (fill loading) or a pressure plate apparatus (assumed to represent vacuum loading), then the specimens were removed and undrained shear strength was measured using a laboratory miniature vane shear device. Considering that in field preloading operations the typical magnitude of maximum vacuum is 80kPa and rarely exceeds 90kPa, and probably in most field conditions, vacuum treated soil remains saturated, the test results and conclusions of Leong et al. (2000) should be treated with caution. Furthermore, the undrained shear strength data reported by Leong et al. (2000) even for the oedometer precompression appears unreasonable except for the data in their Figure 5c for lower marine clay with a preconsolidation pressure of 150kPa (unfortunately, the water content versus log effective stress in their Figure 4c suggests a preconsolidation pressure of about 40kPa).

Dam et al. (2007), following an elaborate derivation that ignores such important factors as σ'_p/σ'_{vo} of soft ground, and that may be applicable only to the boundaries of the treated area, proceeds to generalize that the increase in undrained shear strength near the ground surface from vacuum loading could be 1.5 times greater than that resulting from equivalent fill loading and one-dimensional compression.

3 PRECOMPRESSION BY VACUUM AS A FUNCTION OF DEPTH

For a soft clay layer with constant σ'_p/σ'_{vo} and s_{uo}/σ'_p with depth, and subjected to a constant $\Delta\sigma'_v$ with depth, based on Eq. 1a, the expressions for s_u/s_{uo} in terms of σ'_{vo} and s_{uo}, respectively, are

$$\frac{s_u}{s_{uo}} = \frac{1}{\sigma'_p/\sigma'_{vo}} + \frac{1}{\sigma'_p/\sigma'_{vo}}\frac{\Delta\sigma'_v}{\sigma'_{vo}} \qquad [3a]$$

$$\frac{s_u}{s_{uo}} = \frac{1}{\sigma'_p/\sigma'_{vo}} + \frac{s_{uo}}{\sigma'_p}\frac{\Delta\sigma'_v}{s_{uo}} \qquad [3b]$$

where s_u is undrained shear strength after primary consolidation under $\Delta\sigma'_v$. The relation of s_u/s_{uo} to σ'_{vo} in Eq. 3a or to s_{uo} in Eq. 3b shows that in general s_u/s_{uo} is expected to decrease with depth because σ'_{vo} is a direct indication of depth and s_{uo} may commonly increase with depth, and this type of behavior is not limited to vacuum consolidation.

Qian et al. (1992) reported undrained shear strength increase of 300% at 1.5m and 100% at 8m depth. These measurements of undrained shear strength that correspond to s_u/s_{uo} of 4 and 2, respectively, at 2 and 8m depth can be readily explained in terms of Figure 1.

Yixiong (1996a) reported that during improvement of soft soils at the shore connection for the wharf on the southern side of the East Pier at the Port of Tianjin, China, 25m long prefabricated vertical drains were installed and subjected to about 80kPa vacuum. According to Yixiong (1996a) this was the project having the longest installed vertical drains, which was monitored and tested by Tianjin Port Engineering Institute. The unconfined undrained shear strength, $s_u(UC)$, at depth of 19 to 22.5m and 22.5 to 25m increased, respectively, by 11.5kPa and 11kPa.

Assuming $s_{uo}(UC)/\sigma'_p = 0.25$, $\sigma'_p/\sigma'_{vo} = 1.2$, and $\gamma' = 7\text{kN/m}^3$, and using

$$\Delta s_u(UC) = \frac{s_{uo}}{\sigma'_p}(\sigma'_{vo} + p_v - \sigma'_p) \qquad [4]$$

we obtain at the depth of 19 to 22.5m, $p_v = 75\text{kPa}$, and at depth of 22.5 to 25m, $p_v = 78\text{kPa}$. If the assumptions on soil properties are reasonable, then in fact a vacuum of about of 75 to 78kPa penetrated to the depth of 25m and in the depth range of 19 to 25m the vacuum and associated increase in undrained shear strength were more or less constant with depth.

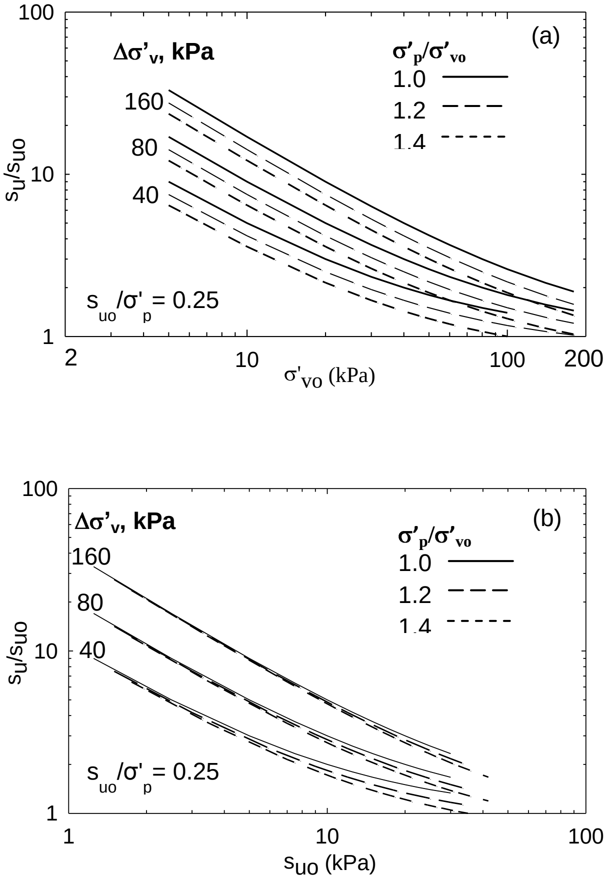


Figure 1. Relation between s_u/s_{uo} and (a) σ'_{vo}, and (b) s_{uo}

Yixiong (1996a), however, proceeded to report that in quite a number of projects involving vacuum preloading, the increase in strength of soil at deeper depth is small and "requires further investigation and studies". For a typical soft clay deposit with σ'_p/σ'_{vo} greater than one, this type of behavior is not limited to vacuum preloading and is also expected for fill preloading, as is illustrated in the following for the same soil assumed in previous paragraphs, together with Eq. 4.

At a depth of 2m, $\Delta s_u(UC) = 19.3\text{kPa}$, $\Delta s_u(UC)/s_{uo}(UC) = 4.60$, and $s_u(UC)/s_{uo}(UC) = 5.60$. At a depth of 20m, $\Delta s_u(UC) = 13.0\text{kPa}$, $\Delta s_u(UC)/s_{uo}(UC) = 0.31$, and $s_u(UC)/s_{uo}(UC) = 1.31$. The same ratios of post-preloading undrained shear strength to pre-preloading undrained shear strength may be obtained from Figure 1 for $\sigma'_p/\sigma'_{vo} = 1.2$, $s_{uo}/\sigma'_p = 0.25$ and $\Delta\sigma'_v = 80\text{kPa}$ which may result either from fill loading or vacuum loading.

Shang and Zhang (1999) reported successful treatment of an 8 meter thick soda-ash tailing with initial water content of 136 to 166% and initial field vane undrained shear strength , s_{uo}(FV), of 7 to 8kPa, using 1.2m spacing and 8m long vertical drains, subjected to 80 to 90kPa vacuum. The field vane undrained shear strength, s_u(FV) of 22 to 27kpa measured after 66 days of vacuum application was more or less constant with depth, especially taking into account the reported average degree of consolidation as a function of depth.

Yan and Chu (2005) presents a detailed report on soil improvement for a storage yard at Tianjin Port, China. The site was divided into three sections for ground improvement. Section II was treated with prefabricated vertical drains at a spacing of 1.0m, to a depth of 20m, and subjected to 80kPa vacuum and 60kPa fill load. Considerable improvement in field vane undrained strength was achieved throughout the entire depth of 16m where field vane tests were conducted. According to Yan and Chu (2005), on average, the vane undrained shear strength increased twofold. This behavior suggests a normally consolidated young soil, i.e. $\sigma'_p/\sigma'_{vo} = 1.0$.

4 DATA ON UNDRAINED SHEAR STRENGTH RESULTING FROM VACUUM CONSOLIDATION

Undrained shear strength data from nine case histories of vacuum consolidation are summarized in Figures 2 – 4, together with undrained shear strength resulting from equivalent vacuum plus fill and fill load and consolidation. In Figure 3, s_u(FV)/s_{uo}(FV) versus s_{uo}(FV) relations from Figure 1 are also plotted, and appear to more or less define the upper and lower bound of the measured behavior. These figures show that undrained shear strength resulting from vacuum consolidation in fact follows the same empirical rules that have resulted from fill loading and consolidation; e.g. for a given vacuum load, s_u(FV)/s_{uo}(FV) increases dramatically with the decrease in s_{uo}(FV).

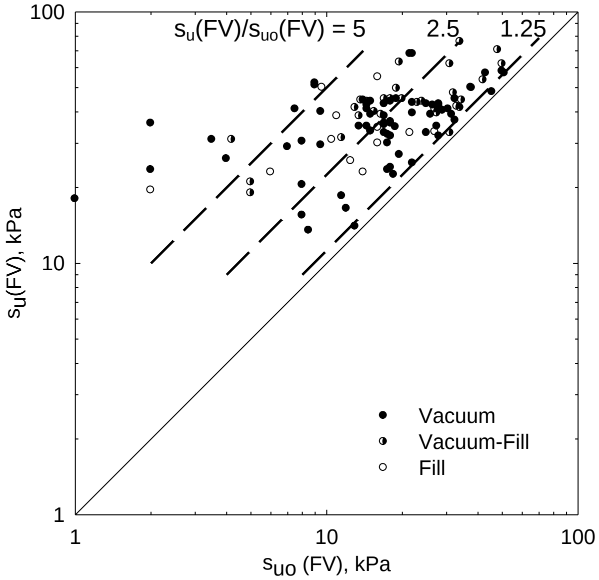


Figure 2. s_u(FV) for vacuum, vacuum plus fill and fill loading

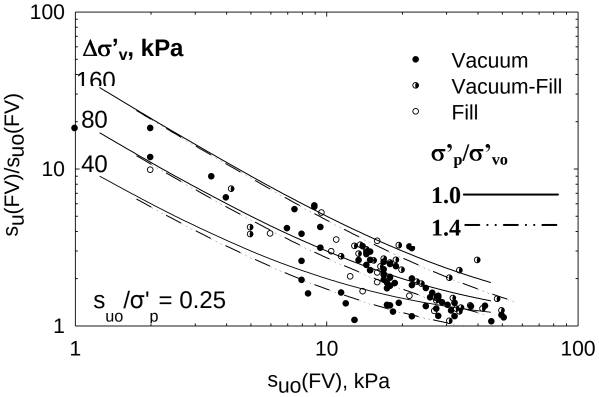


Figure 3. s_u(FV)/s_{uo}(FV) as a function of s_{uo}(FV)

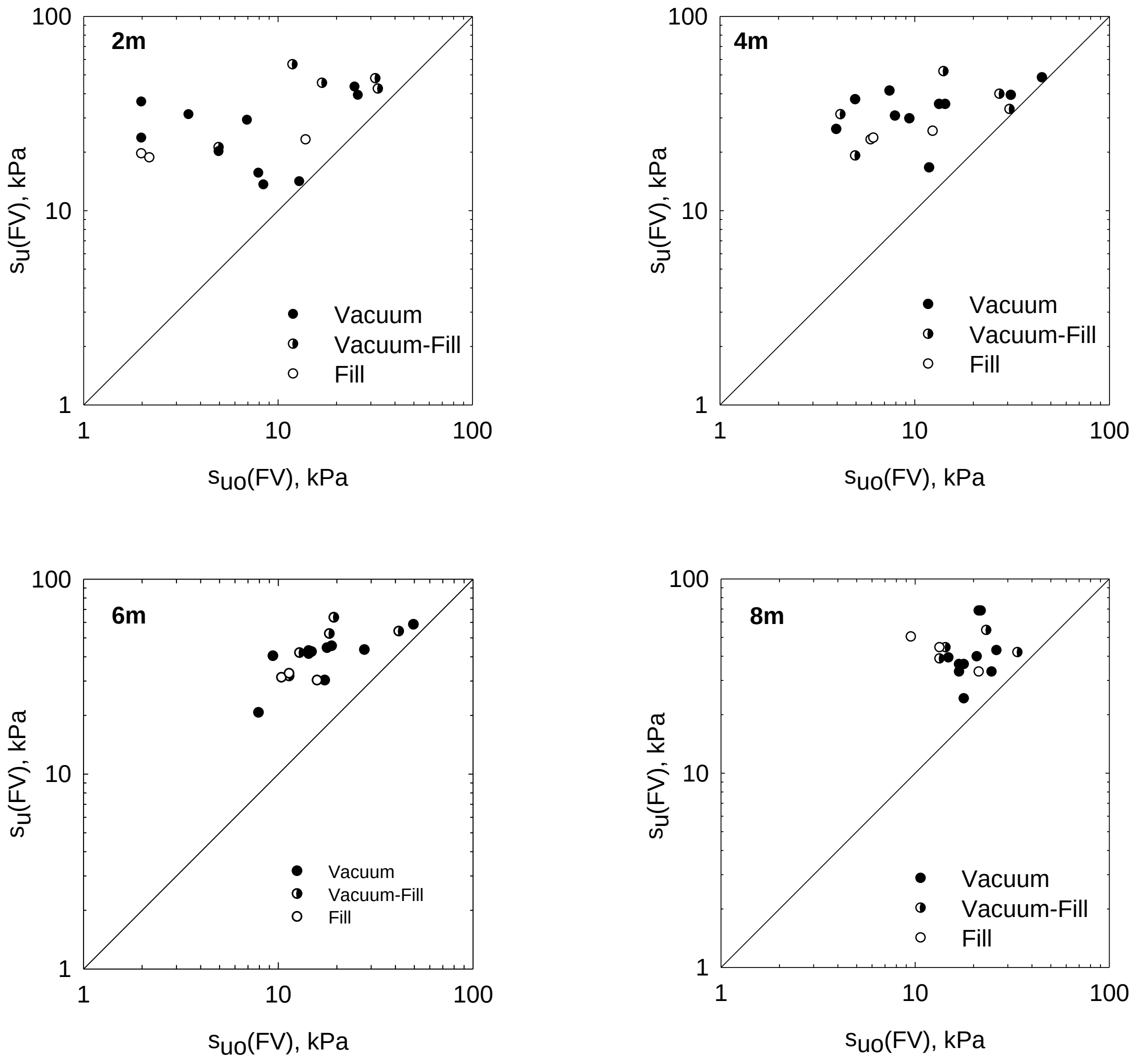
In Figure 2 the vertical distance of the data points from the 45 degree line defines (s_u-s_{uo}). Equation 3b may be rewritten as

$$s_u - s_{uo} = \left[\Delta\sigma'_v - (\sigma'_p - \sigma'_{vo})\right]\frac{s_{uo}}{\sigma'_p} \tag{5a}$$

or $$s_u - s_{uo} = \left[\Delta\sigma'_v - \frac{1}{\sigma'_{vo}}\left(\frac{\sigma'_p}{\sigma'_{vo}} - 1\right)\right]\frac{s_{uo}}{\sigma'_p} \tag{5b}$$

In a soft ground where the behavior of preconsolidation pressure, σ'_p, with depth is best defined by a constant (σ'_p - σ'_{vo}) with depth, then Eq. 5a shows that for both fill loading and vacuum loading, (s_u – s_{uo}) is expected to be constant with depth. On the other hand in case the behavior of σ'_p with depth is best defined by a constant σ'_p/σ'_{vo} with depth, then Eq. 5b shows that for both fill loading and vacuum loading, (s_u – s_{uo}) is expected to decrease with depth. The undrained shear strength data from the nine case histories are shown in Figure 4, separated for a depth range of 2 to 16m. These data appear to suggest for these soft grounds, σ'_p/σ'_{vo} constant with depth as opposed to (σ'_p - σ'_{vo}) constant with depth. A constant σ'_p/σ'_{vo} with depth often results from aging (e.g. secondary compression), whereas a constant (σ'_p - σ'_{vo}) with depth may result from ground surface loading and unloading.

For the land reclamation at the East pier of Xingang Port in Tianjin, China, reported by Choa (1989, 1990), Yixiong (1996a, b) and Shang et al. (1998), and briefly summarized in a previous section of this paper, data are available as a function of depth for plasticity index, I_p, and pre-ground treatment σ'_{vo} and s_{uo}(FV). These data together with $s_{uo}(FV)/\sigma'_p$ versus I_p relationship (Fig. 20.20 of Soil Mechanics in Engineering Practice, Terzaghi et al. 1996) can be used to determine σ'_p/σ'_{vo} with depth. Thus Eq. 3a together with σ'_p/σ'_{vo} and $\Delta\sigma'_v/\sigma'_{vo}$ were used to



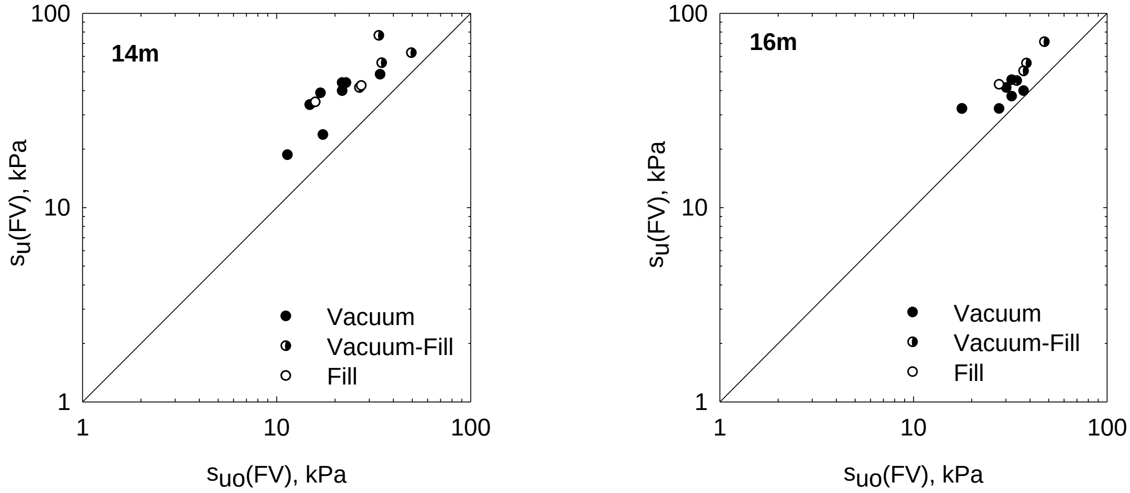


Figure 4. s_u(FV)/s_{uo}(FV) as a function of depth

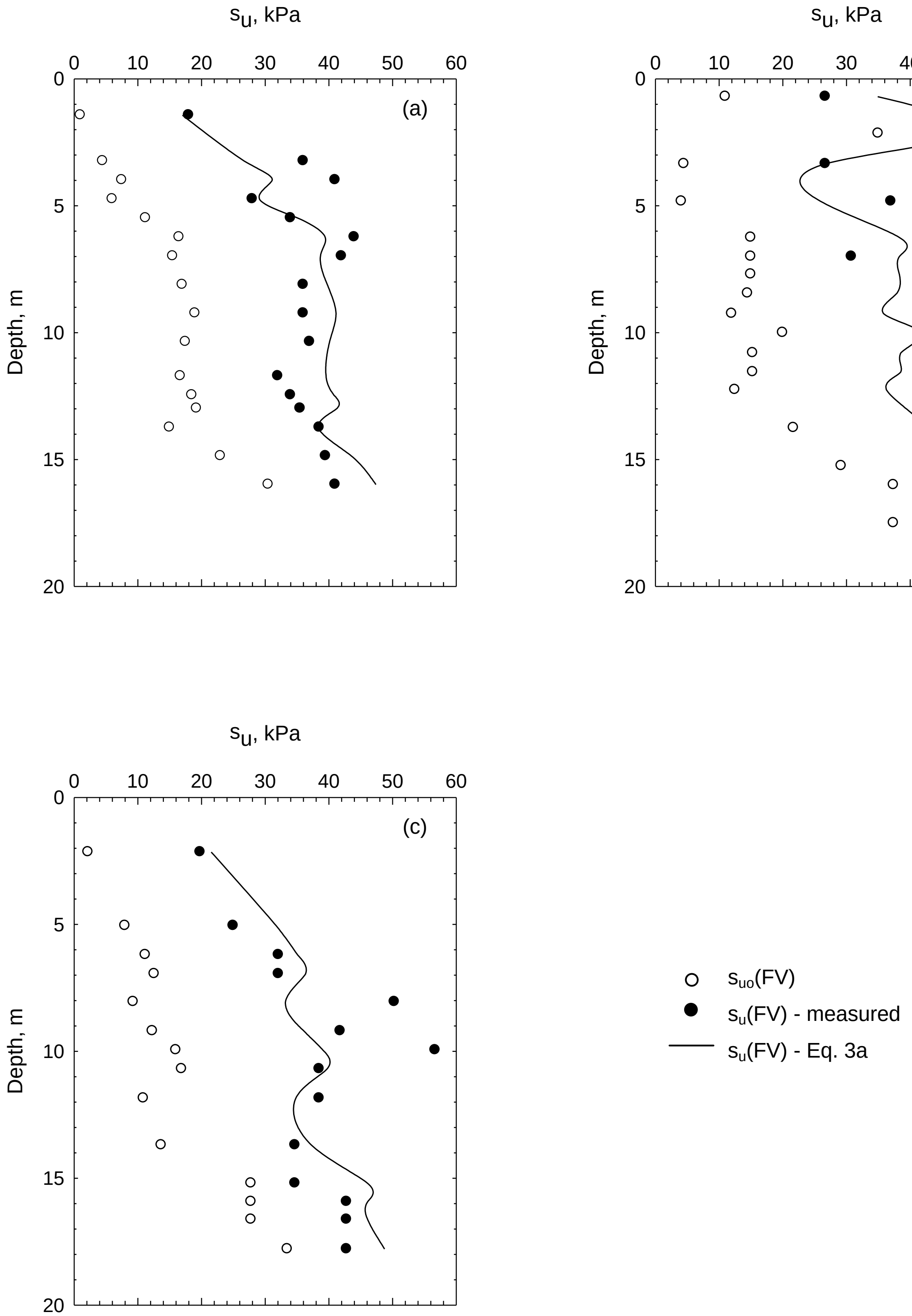


Figure 5. Measurement and prediction of su(FV) for (a) vacuum load, (b) vacuum plus fill load, and (c) fill load

predict s_u(FV) for subdivisions 12-13, 44, and S-2, and are compared with measurements in Figure 5. For all three cases of vacuum loading, vacuum plus fill loading, and fill loading, there is acceptable agreement between the predictions and measurements.

5 CONCLUSIONS

The following conclusions are based on the analyses, data, and interpretation presented in this paper.

One distinct advantage of preloading using vacuum as compared to preloading by fill is the increase in undrained shear strength without the possibility of undrained bearing capacity failure during the preloading operation.

All empirical concepts concerning undrained shear strength of soft clay and silt deposits that have been developed based on fill loading are equally applicable to vacuum loading.

The increases in undrained shear strength of soft clay and silt deposits resulting from consolidation under a vacuum load and equivalent fill load, for all practical purposes, are identical.

For soft clay and silt deposits subjected to a constant increase in effective vertical stress with depth, resulting from either a vacuum load or fill load, , s_u/s_{uo} decreases with the increase in σ'_{vo} (depth) or increase in s_{uo} (which is likely to increase with depth).

The increase in undrained shear strength ($s_u - s_{uo}$), of soft clay and silt deposits subjected to a constant increase in effective vertical stress with depth, resulting from either vacuum load or fill load, is expected to remain constant with depth for soil profiles with either $\sigma'_p/\sigma'_{vo} = 1$ or ($\sigma'_p - \sigma'_{vo}$) = constant with depth.

The increase in undrained shear strength ($s_u - s_{uo}$), of soft clay and silt deposits subjected to a constant increase in effective vertical stress with depth, resulting from either vacuum load or fill load, is expected to decrease with σ'_{vo} (depth) for soil profiles with σ'_p/σ'_{vo} greater than one.

With subsurface information on vertical profiles of σ'_p/σ'_{vo}, s_{uo}/σ'_p, and $\Delta\sigma'_v$ resulting from vacuum, vacuum plus fill, and fill loading, vertical profile of the increase in undrained shear strength can be predicted. Note that $\Delta\sigma'_v$ may represent increase in effective stress before or at the end of primary consolidation and therefore may be variable or constant with depth for vacuum consolidation.

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