Minimum effective PV drain spacing from embankment field tests in soft clay

Espacement minimum effectif pour des drains PV obtenu a partir d'essaisde remblai en vrai grandeur dans une argile molle

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ABSTRACT
The effect of soil disturbance on prefabricated vertical drain efficiency was investigated using six test areas with drain spacings ranging from 0.9 m to 2 m under an embankment on soft clay. Fill placement and settlement time histories were monitored. The computed total settlement at each measurement location was typically within ± 20%, with an average error of 14%. The rate of consolidation increased as spacing decreased until spacing decreased below 1.22 m. At this point disturbance effects cancelled benefits from closer spacing for the clay and anchor system involved. These results combined with other case histories provide evidence that drain performance will be adversely affected when the drain spacing divided by the equivalent mandrel diameter is less than about 8.

RÉSUMÉ
L'effet de perturbation du sol sur l'efficacité drain vertical préfabriqué a été étudiée en utilisant six zones de test avec des espacements de vidange à partir de 0,9 m à 2 m dans le cadre d'un remblai sur argile molle. Le placement du rembourrage et le règlement du temps ont été surveillés. Le règlement total calculé à chaque emplacement de mesure est typiquement de ± 20%, avec une erreur moyenne de 14%. Le taux d'augmentation de l'espacement de consolidation s'est agrandi lorsque l'espacement diminuait jusqu'a ce que l'espacement diminué soit au-dessous 1,22 m. À ce point les effets de perturbation ont annulé les avantages de l'espacement de plus près pour l'argile et de l'ancre du système en cause. Ces résultats combinés à d'autres cas fournissent preuve que les histoires drain performance seront mal affectée lorsque la vidange d'espacement, divisé par le mandrin de diamètre équivalent soit inférieur à 8.

Keywords : prefabricated vertical drains, consolidation, settlement, soil disturbance, field tests

1 INTRODUCTION

Although consolidation theory indicates that clay layers will consolidate faster as vertical drain spacing decreases, investigators have noted the detrimental effects of installation disturbance for many years (Barron 1948, Hansbo 1979). During the Interstate 15 design-build project in Salt Lake Valley field tests indicated that prefabricated vertical (PV) drain spacings closer than about 1.75 m did not provide any additional benefit (Saye et al. 2001). Apparently, disturbance of the sensitive clay due to installation of the drain reduced the permeability in the smear zone around the drains sufficiently to overcome any benefit from the closer spacing. However, this minimum effective spacing or "critical drain spacing" is related to soil sensitivity as well as the geometry of the anchor and mandrel. For smaller anchor/mandrel geometries, the drain spacing could potentially be decreased with corresponding benefits. To evaluate this possibility, additional field tests were carried out at the Salt Lake International Airport using a mandrel/anchor geometry with a smaller area than was used on the Interstate 15 project. As expansion of Interstate 15 and other roadways continues on soft clays in Utah, reliance on the 1.75 m minimum spacing criteria could lead to unnecessarily long construction times and therefore, higher construction costs. The test program was aimed at developing improved models to account for the effect of smear zones on the performance of PV drains in soft clays.

2 FIELD TEST LAYOUT AND INSTRUMENTATION

During 2004, the Salt Lake City International Airport constructed a new bridge in connection with a parking expansion project. The bridge abutment was 8.2 m tall at the highest point and sloped down to a height of about 3.3 m to join the existing roadway. Area 1 drain spacing was 1.22 m while in Area 2 spacing was 2.04 m. Settlement in both areas was monitored with manometer type settlement gauges as part of the construction contract. In addition, four additional test areas were constructed to evaluate variation in drain spacings from 0.91 m to 2.04 m as shown in Figure 1. Each test area was about 15.25 m square and had a settlement gauge near its center. The centers of the four test areas were positioned so that the average fill heights would be comparable. The PV drains (100 mm x 6 mm) in each area were identical and were installed using the mandrel/anchor section illustrated in Figure 2. The drains were anchored with a 15 cm x 7.5 cm aluminum anchor plate (4 mm thickness). These anchors are smaller than those previously used for the I-15 project as illustrated in Figure 2.

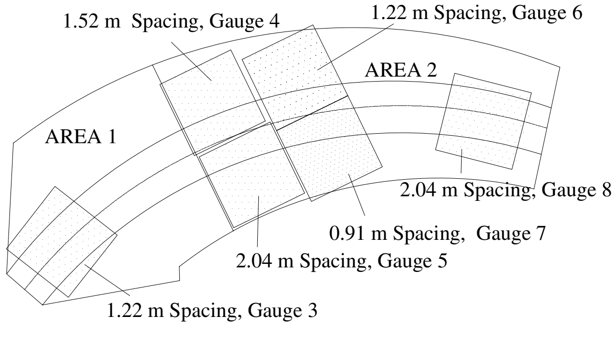

Figure 1. Layout of PV drain test areas and settlement gauges relative to approach fill geometry.

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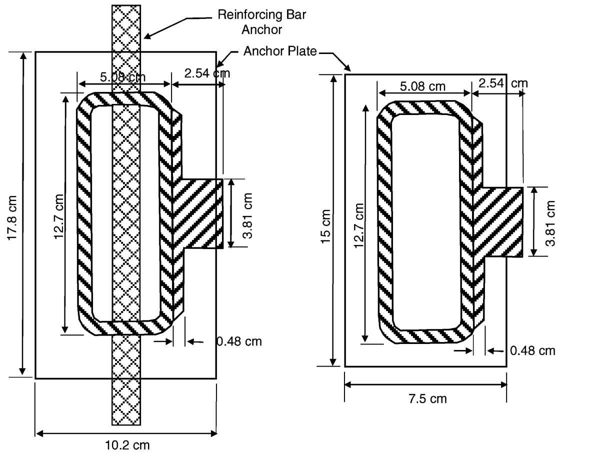
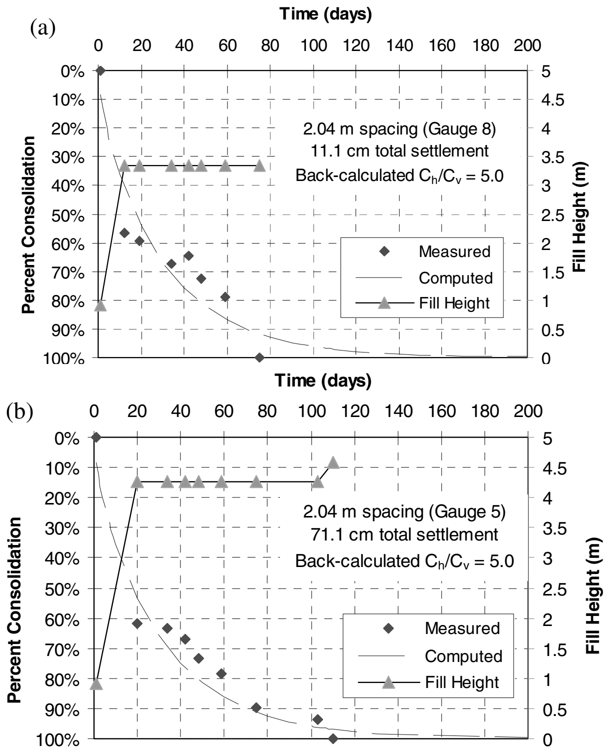


(a) I-15 Mandrel/Anchor (b) SLC Airport Mandrel/Anchor

Figure 2. Geometry of mandrel and anchor plates used to install vertical PV drains at (a) I-15 test site (b) SLC Airport test site

3 FIELD TEST RESULTS

Percent consolidation versus time plots for the various test areas are provided in Figure 3 along with fill height vs. time. Total settlements are listed on each plot and ranged from 12 to 26 cm. The t_{95} times varied from 50 to 100 days. The gauges, which were monitored by the contractor, were not read as frequently as might be desired and there are some aberrations in the data likely due to settlement of the reference shacks. In addition, the total settlement from gauge 5 was not reliable although the normalized settlement appears reasonable. Nevertheless, the data still provide useful information as will be discussed subsequently. The t_{95} times are plotted as a function of drain spacing in Figure 4. Generally, the t_{95} times decreased as drain spacing decreased from 2.04 to 1.22 m, but for closer spacings, the t_{95} times remained relatively constant or even increased slightly. These results suggest that the "minimum effective drain spacing" is about 1.22 m. Similar data from previous embankment tests on Salt Lake Valley clay conducted by Saye et al. (2001) are also shown in Figure 4 for comparison.



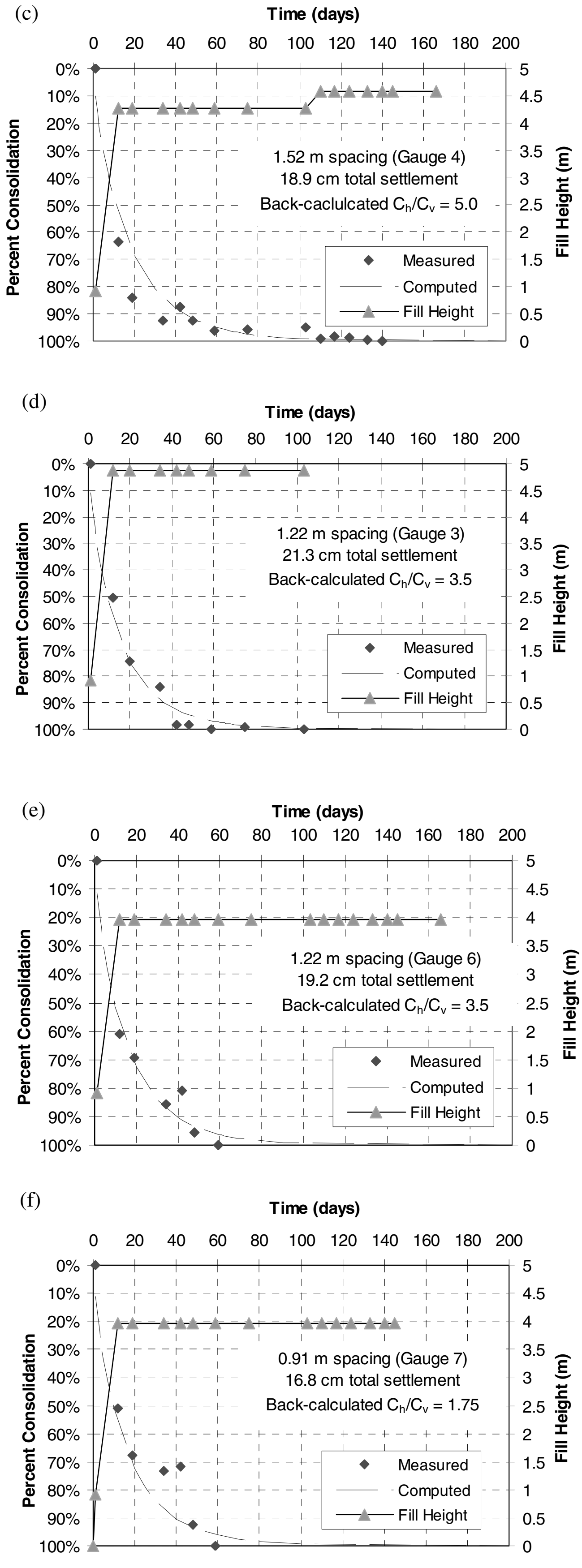


Figure 3. Plots of fill height vs. time along with measured and computed percent consolidation vs. time curve for drains spacings of (a) 2.04 m, (b) 2.04m, (c) 1.52 m, (d) 1.22 m, (e) 1.22 m, and (f) 0.91 m.

As noted previously, the minimum effective spacing in previous tests was 1.75 m. The greater minimum effective spacing is likely associated with the greater cross sectional area/effective diameter of the mandrel/anchor combination used in the previous study (181 cm^2/17.8 cm) relative to that in this study (116 cm^2/15.4 cm).

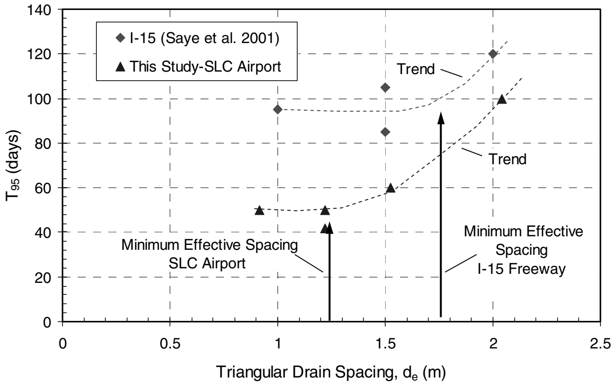


Figure 4. Variation of t_{95} with PV drain spacing for this study and previous study for I-15 in Salt Lake Valley, Utah (Saye et al. 2001).

4 ANALYSIS OF FIELD TEST RESULTS

4.1 *Idealized soil profile and properties*

The total settlement and time-rate of settlement calculations for each test area were performed using the idealized soil profile developed during the original site investigation (RBG Engineering, 2003). The generalized soil profile is shown in Figure 5 and the soil properties for each layer obtained from soil testing are summarized in Table 1. The C_v values are consistent with the values obtained from the MIT oedometer testing (Saye et al. 2001) and with back-calculated field performance for embankments in Salt Lake Valley.

Table 1 Soil parameters of idealized soil profile.

Depth (m)	Soil Type	Re-Comp. Index C_s	Comp. Index C_c	Total Unit weight, γ (kN/m^3)	Void Ratio, e	Consol. Coeff. C_v (m^2/day)
1-3	CL	0.04	0.54	17.4	1.095	0.0093
3-4.6	CL	0.04	0.445	17.5	1.10	0.0093
4.6-6.4	SP	NA	NA	19.6	0.67	NA
6.4-7.3	CH	0.07	0.505	17.4	1.25	0.0028
7.3-8.8	SP	NA	NA	19.6	0.67	NA
8.8-10.1	CL	0.015	0.285	19.5	0.755	0.0083
10.1-10.4	SP	NA	NA	19.6	0.67	NA
10.4-13.4	CL	0.036	0.30	18.8	0.85	0.0083

4.2 *Total settlement calculations*

The consolidation settlement was computed using the following well-known equations for normally consolidated clay layers,

$$S_c = \frac{C_c H}{1+e_o}\log\left(\frac{\sigma'_o+\Delta\sigma}{\sigma'_o}\right) \quad (1)$$

for over-consolidated layers where $\sigma_o'+\Delta\sigma < \sigma_c'$

$$S_c = \frac{C_r H}{1+e_o}\log\left(\frac{\sigma'_o+\Delta\sigma}{\sigma'_o}\right) \quad (2)$$

and overconsolidated layers with $\sigma_o'+\Delta\sigma > \sigma_c'$

$$S_c = \frac{C_r H}{1+e_o}\log\left(\frac{\sigma'_c}{\sigma'_o}\right) + \frac{C_c H}{1+e_o}\log\left(\frac{\sigma'_o+\Delta\sigma}{\sigma'_c}\right) \quad (3)$$

where C_c is the compression index, C_s is the re-compression index, e_o is the initial void ratio, H is the total thickness of the layer, σ_o' is the initial vertical effective stress, Δσ is the induced stress due to the embankment load, and σ_c' is the pre-consolidation pressure.

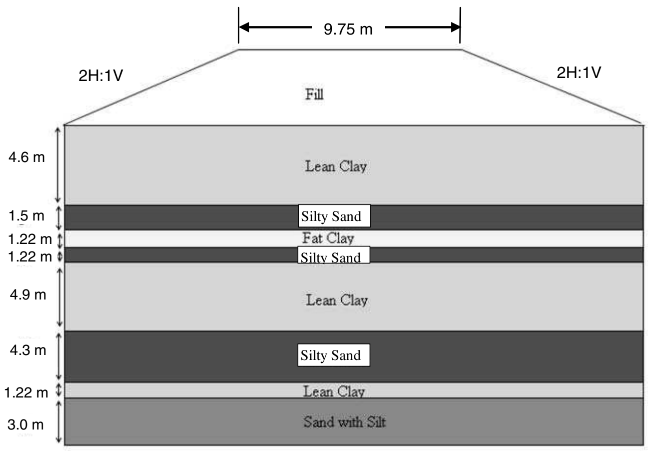


Figure 5. Idealized soil profile below abutment fill based on soil boring logs.

To calculate total settlement, the clay layers were sub-divided into smaller intervals to account better for variations in induced stress and pre-consolidation pressure values. The pre-consolidation pressure profile used in the analysis was based on the soil test data and had a shape typical of a clay profile with a desiccated crust. The lean clay from 0 to 4.6 m depth was overconsolidated, the fat clay was normally consolidated and the lower lean clay layers were somewhat overconsolidated. The total computed settlement for each test area is compared with the measured settlement in Figure 6. On average the computed settlement was within 14% and predicted settlement was typically within ± 20% of the measured value.

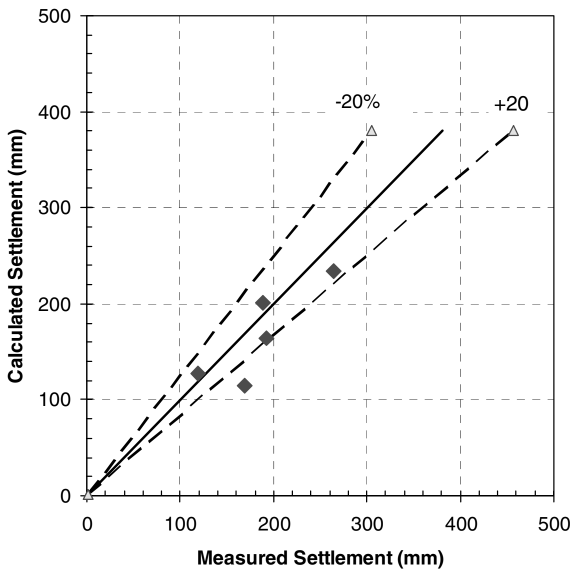


Figure 6. Comparison of measured and computed settlement for the five test areas.

4.3 *Time-rate of settlement calculations*

The time-rate of settlement was computed for each test area by accounting for both radial and vertical consolidation. The total degree of consolidation (U) for a layer is given by the equation

$$U = (1-U_v)(1-U_r) \quad (4)$$

where U_v and U_r are the degree of consolidation due to vertical and radial drainage, respectively. U_v is dependent on the layer thickness, H and the vertical coefficient of consolidation, C_v, for each layer which are provided in Table 1. According to Barron (1948), U_r is dependent on the drain spacing, d_e, the PV drain diameter, and the horizontal coefficient of consolidation, C_h. Previous studies on Salt Lake clays conducted by Saye et al. (2001) found C_h to be about four to five times C_v for widely spaced drains. A C_h/C_v ratio of 4 was initially assumed and then modified as necessary to obtain the best fits with the measured data. The computed settlement as a function of time was obtained by multiplying the computed degree of consolidation for each layer by the computed settlement for the layer and then summing up the settlements for each layer. This settlement was then divided by the total predicted settlement to obtain a normalized settlement vs. time curve. These computed percent consolidation vs. time curves are compared with the measured data points in Figure 3. The actual C_h/C_v ratio is provided on each consolidation-time plot.

As shown in Figure 3, the back-calculated C_h/C_v ratios decreased from 5 to 3.5 as drain spacing decreased from 2.04 m to 1.54 m and produced good agreement with the measured data points. In fact, a ratio of 4 for all these spacings produced reasonably good agreement. However, as drain spacing decreased to 0.9 m, it was necessary to decrease the C_h/C_v ratio to 1.75 to obtain better agreement with the measured consolidation vs. time data points. The lower ratio is likely a result of increased disturbance produced by insertion of the mandrel/anchor system at closer spacing.

5 COMPARISON WITH PREVIOUS STUDIES

Saye (2001) plotted back-calculated C_h/C_v ratios as a function of normalized drain spacing for a number of case histories involving PV drains as well as sand drains as presented in Figure 7. In this figure, the drain spacing has been normalized by the equivalent diameter, d_m, of the mandrel/anchor arrangement. The d_m value is defined as the perimeter around the mandrel/anchor cross-section divided by π.

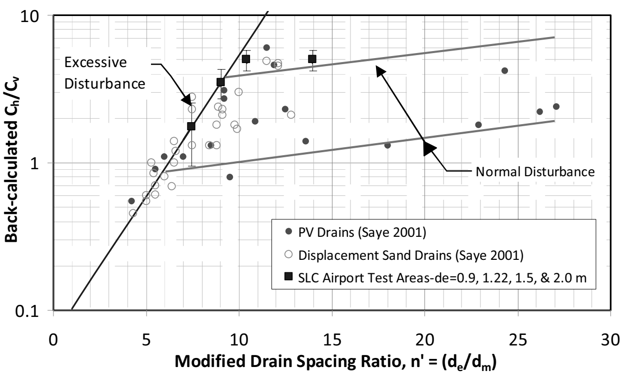


Figure 7. Back-calculated C_h/C_v ratios versus modified drain spacing ratio for prefabricated and sand drains along with ratios from SLC Airport embankment test areas.

Saye (2001) found that the C_h/C_v ratios decreased very little for normalized spacings greater than 7 to 9; however, for normalized spacings less than about 7 the ratios began to decrease much more rapidly. This ratio indicates the transition zone where soil disturbance from mandrel/anchor insertion starts to significantly degrade the performance of the PV drain. The back-calculated C_h/C_v ratios obtained from this study are also plotted in Figure 7 (with uncertainty bars). The data are consistent with the trends obtained from other field case histories, although they are at the high end of the ranges. In addition, the back-calculated C_h/C_v ratios decrease more significantly at a normalized spacing of 7.5 as would be expected. These results suggest that mandrel disturbance effects can be reasonably predicted using this normalized spacing concept which accounts for variations in mandrel/anchor geometries.

6 CONCLUSIONS

Based on the results of the field tests and the analysis of the test results, the following conclusions can be drawn:

1. Using consistent soil profiles and properties but accounting for differences in induced stress, the predicted total settlement at each measurement location was typically within ± 20% with an average error of 14%.
2. The results from the Salt Lake City Airport tests indicate that a minimum effective drain spacing does exist and that it is between 0.9 m and 1.22 m for the soil types and mandrel/anchor ($A=116\ cm^2$, $d_m=15.4$ cm) involved. This is a reduction of about 0.5 m from the minimum effective drain spacing selected for the I-15 project. The improvement in PV drain efficiency is likely attributable to a smaller anchor area.
3. The effect of installation disturbance on the consolidation versus time curves could be reasonably accounted for based on the modified drain spacing concept developed by Saye (2001). Back-calculated C_h/C_v values were relatively constant (≈4) until the spacing ratio decreased to 7.5 at which point a significant drop was observed. These results provide additional evidence that drain performance will be adversely affected by modified drain spacing ratios less than about 8.

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REFERENCES

Barron, R.A. 1948. "*Consolidation of fine-grained soils by drain wells*". Trans. ASCE, 113, p. 718.

Hansbo, S. 1979. "*Consolidation of clay by band shaped prefabricated drains.*" Ground Engineering, Vol. 12, No. 5, p. 21-25.

RBG Engineering, Inc. 2003. "*South Bar Flyover Bridge and Approach Fills, Salt Lake City International Airport, Salt Lake City, Utah*". 18. p.

Saye, S.R. 2001. "*Assessment of soil disturbance by the installation of displacement sand drains and prefabricated vertical drains*". Soil Behavior and Soft Ground Construction, GSP 119, ASCE, p. 325-362.

Saye, S.R., Ladd, C.C., Gerhart, P.C., Pilz, J., and Volk, 2001. "*Embankment construction in an urban area: the Interstate 15 experience*". Foundations and Ground Improvements, GSP 113, ASCE, 842-857.