DISCUSSION of:

Ground Improvement Using Preloading with Prefabricated Vertical Drains

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INTRODUCTION

The authors have presented a straightforward case history on settlements measured for a wick drain preloading project; not from a specific research project but from an actual engineering project. The latter fact makes up for some lack of details. Nevertheless, it would be desirable if the authors could supply the following additional information.

1. a delineated figure similar to authors' Figure 2 showing which part—about a third of the total project site—that was included in the reported measurements.

2. a delineated figure similar to authors' Figure 11 showing the locations of the 12 settlement observation benchmarks included in the authors' Figure 13.

3. a table indicating the measured or estimated thickness of the clay layer for each of the 12 settlement benchmarks.

4. an estimate of the immediate settlements of the four soil layers due to the placing of the surcharge that preceded the consolidation settlement of the clay layer.

The authors report, that the first survey of the benchmarks was taken before the 3.0-m surcharge was placed across the test area. The first day of settlement measurements for the twelve benchmarks was the date of the second benchmark survey, which was carried out only when all of the surcharge had been placed to the full height over the test area. The time between the first and second surveys—and the placing of the surcharge—ranged from a few days to twenty days. Because the times between the placing of the surcharge and the second survey differed for the benchmarks, the amount of settlement that had occurred at the time of the second survey also differed between the benchmarks. This explains some of the significant scatter displayed in the authors' Figure 13. I have re-plotted the measured settlements in Figure 1 to a common starting point at the average start settlement of 160mm and added 10 days to the authors' measurement days to indicate the average duration of placing the surcharge, which took place before the second survey. During this time, immediate compression and some consolidation will have occurred. As indicated, I estimate the immediate compression to be about 50 mm. I have also added an average curve and extrapolated it back to the origin (the average excludes the two outlier records). All benchmarks appear to show that most of the consolidation had developed at the time the last survey was made.

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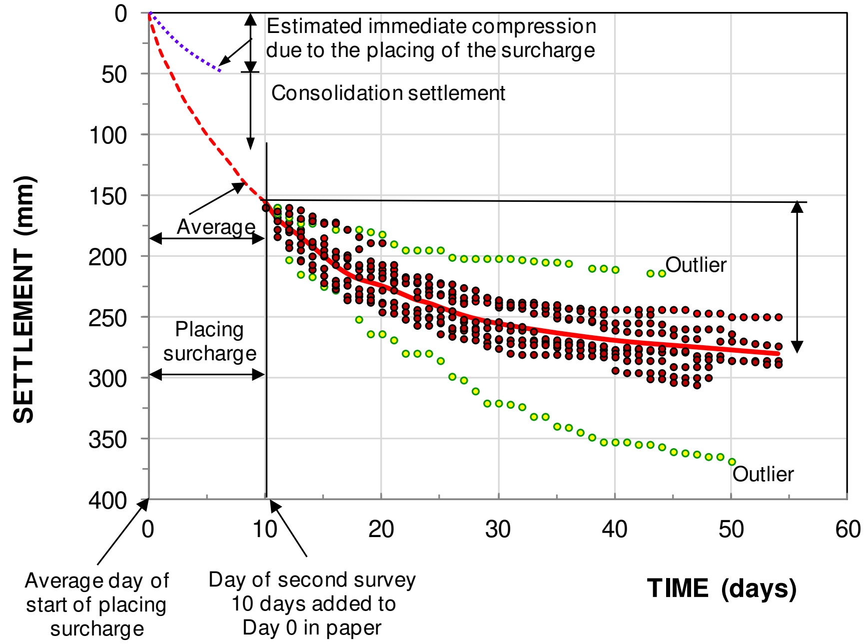

Figure 1. Settlement measured at the benchmarks shifted 10 days.

Figure 2 shows the measured final settlements are normalized to the average final settlement (280 mm). There is still much scatter between the curves, but now the approximate start date for each curve can be obtained by sliding the curves left or right until the best agreement to the average curve is obtained as shown in Figure 3. The removal of much of the scatter—the agreement between the time-settlement curves—is of course to some extent fictitious as the benchmark measurements cannot be expected to be all that similar; a natural variation must have taken place, not least with regard to the thickness of the soft clay layer. However, I believe that the figure suggests a reasonably realistic day for the start of placing the surcharge.

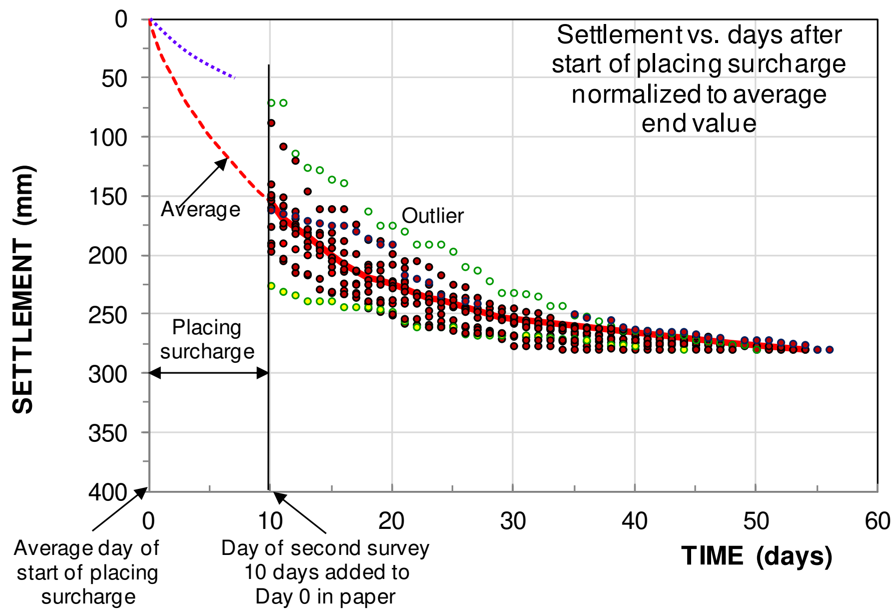

Figure 2. Settlement measured at the benchmarks normalized to the average end values.

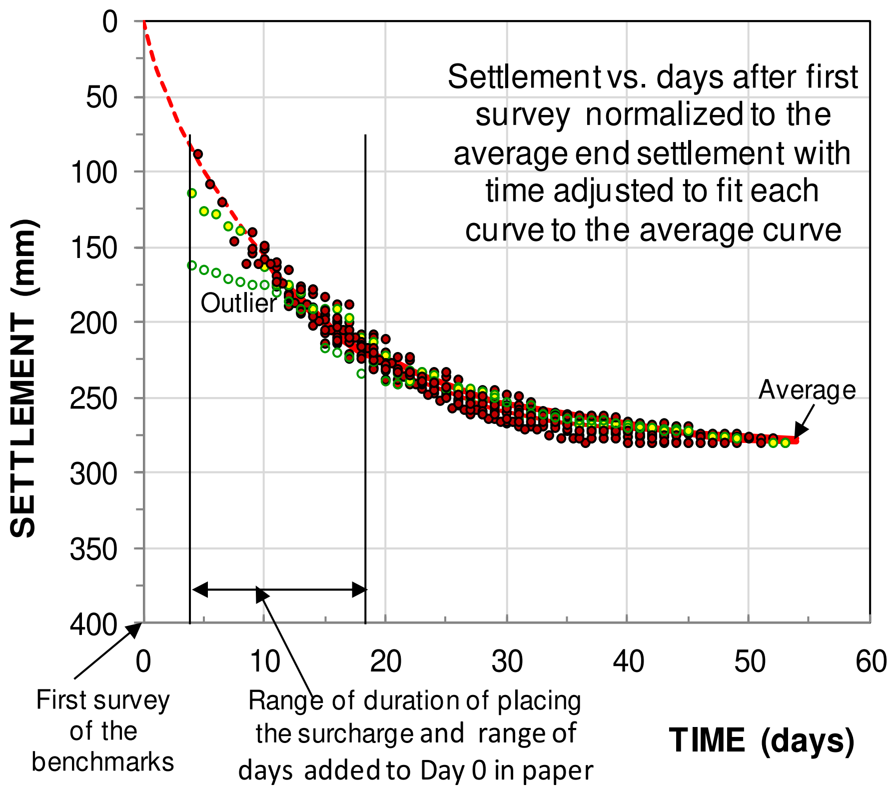

Figure 3. Settlement measured at the benchmarks adjusted to obtain the approximate start day.

The average curve shown in Figure 3 can now serve as reference to a back-calculation of the time-settlement development for the wick-drain project to determine compressibility and coefficient of consolidation of the soil layers. The back-calculation consists of applying the theory of pore pressure dissipation in fine-grained soils (consolidation) due to radial flow (Barron 1948, Kjellman 1948, and Hansbo 1960; 1979) is based on radial flow toward a circular drain in the center of a cylinder of homogeneous soil with an impervious outer boundary surface). The theory is summarized in the Kjellman-Barron formula, Equation 1. The Kjellman-Barron formula is based on the assumption of horizontal (radial) flow only and a homogeneous soil.

$$t = \frac{D^2}{8c_h}\left[\ln\frac{D}{d} - 0.75\right]\ln\frac{1}{1-U_h} \qquad (1)$$

where
- t = time from start of consolidation (s)
- D = zone of influence of a drain (m)
- d = equivalent diameter of a drain (m)
- U_h = average degree of consolidation for radial (horizontal) flow (--)
- c_h = coefficient of horizontal consolidation (m^2/s)
  ($1\ m^2/s = 3.2 \times 10^8\ m^2/year$)

Equation 1 can be rearranged to give Equation 2, the relation for the average degree of consolidation, U_h, which is the same equation as the Authors' Equations 4 and 5 with the portions on smear and discharge capacity (well resistance) removed.

$$U_h = 1 - \exp\left[\frac{-8\, c_h\, t}{D^2\,(\ln\frac{D}{d} - 0.75)}\right] \tag{2}$$

The horizontal drainage achieved by installing vertical drains will accelerate the consolidation settlement to a approximate factor equal to the square of the ratio between the thickness of the soil layer and the spacing of the drains, times the ratio of the vertical and horizontal coefficients of consolidation. Of course, the vertical drainage occurs together with the horizontal drainage. Asaoka (1978) presented a relation for the combined effect as quoted in Equation 3. Usually, the thickness of the consolidating soil layer is many times larger than the spacing of the vertical drains. The vertical drainage is then omitted from the analysis.

$$U_c = 1 - (1 - U_h)(1 - U_v) \tag{3}$$

where U_c = average degree of consolidation, combined
U_h = average degree of consolidation, horizontal only
U_v = average degree of consolidation, vertical only

The theory of consolidation applied to vertical drains is based on the assumption of a circular drain. In applying it to a wick drain, which is a bandshaped drain, the drain must be converted to a virtual "sand" drain, that is, to a circular shape. This is usually, as reported by the authors, done by the input of an equivalent diameter, "d", with a circumference equal to the total circumference of the wick drain. The authors applied this definition, which results in a 66-mm equivalent drain diameter. However, other approaches for determining the equivalent diameter have been proposed, e.g., assuming that "d" is equal to the average of the width and thickness of the wick drain, resulting in a 52mm diameter for the subject drain. Or, that the equivalent sand drain diameter of the wick drain is that of a drain with the same open area as its virtual sand drain (Fellenius 1977). The ratio of open and obstructed area of a sand drain is equal to the porosity of the sand, about 0.40. The wick drain has a much larger open surface ratio than a sand drain, the ratio is about 0.70, depending on wick drain type. Accordingly, for the subject drain, the equivalent gross sand drain diameter would be equal to 208x0.70/0.40π = 116mm.

As the authors report, the width of the smear zone reported in different studies ranges significantly between various writers. The zone is a function of several factors, not least the gross cross section of the installation mandrel as opposed to the drain cross section, which the authors report to have been $70cm^2$, as opposed to the $4cm^2$ drain cross section. On withdrawal of the mandrel, the soil that was displaced and "smeared" by inserting the mandrel is assumed to flow back against the drain and, in the process, the permeability of the soil is reduced in a zone, the smear zone, nearest the drain. However, it has been argued that, in some soils, the displacement and flow-back result in opening up of fissures in the soil that provide improved passages for the water and, therefore, the "disturbance" actually increases the flow characteristics of the soil. The relative importance of the smear zone is also a function of the drain spacing and reduces with increased spacing. A 1.4-m drain spacing may well result in about the same time development as a 1.0-m spacing. The former would require only half as much total length of drain as the latter.

The questions of the widths of the equivalent sand drain and the smear zone are not possible to assess in a field study unless the study includes different size drains and different spacing between the drains. The subject study involves no such parameter variation and can therefore neither be used to draw any conclusions as to a correct equivalent drain diameter nor thickness of smear zone to use when back-calculating the results to find the soil compressibility and coefficient of consolidation. Moreover, the measurements do not separate the immediate compression from the consolidation settlement and the fact that the actual thickness of the soft clay layer ranged from 3 through 7m make for a source of additional uncertainty in using the records for detailed theoretical assessment. For the back-calculation, I have assumed a 5-m thickness of the clay layer. I also applied a 66-mm equivalent circular drain diameter.

I believe that a reasonable, albeit approximate, modulus of immediate compressibility of the four soil layers is about 30MPa, the same for each layer, which results in an immediate compression of 50 mm, as indicated in the figures. (Settlement due to secondary compression will have been negligible). Thus, the measured average consolidation settlement is 230mm, occurring only in the soft clay layer. The back-calculated Janbu modulus number for the soft clay is 18, characterizing it as moderately compressible. The authors indicate an average value of, C_c, for the clay of 0.3. Combining this with the back-calculated modulus number, results in a void ratio of 1.38, which lies within the 1.04 through 1.62 range of void ratio presented by the authors.

The next step of back-calculation was fitting calculated development of settlement over time to the measured settlement. I assumed that the surcharge (stress) was placed in four steps of 14kPa, the first step coinciding with the placing of final 200-mm of the drainage blanket and the other three loading events following every two to three days later. A next to perfect fit was obtained with a c_h-coefficient of 11 m^2/year combined with a c_v-coefficient of 7.5 m^2/year (the latter is the authors' laboratory value. However, including the vertical drainage or excluding it made very little difference to the fit). All calculations were made with the UniSettle4 software (Goudreault and Fellenius 2011).

The results of the back calculation are shown in Figure 4 together with the average curve of the measurements. In order to show the sensitivity of the clay layer thickness and modulus number, the figure also shows the final settlement for soil layer thickness ranging from 3 through 7m and the final settlement resulting from modulus numbers of 15 and 21. The figure also shows the settlement during the first 60 days that would have occurred had there been no wick drains (for this input, I used the authors' 7. 5m^2/year c_v-coefficient).

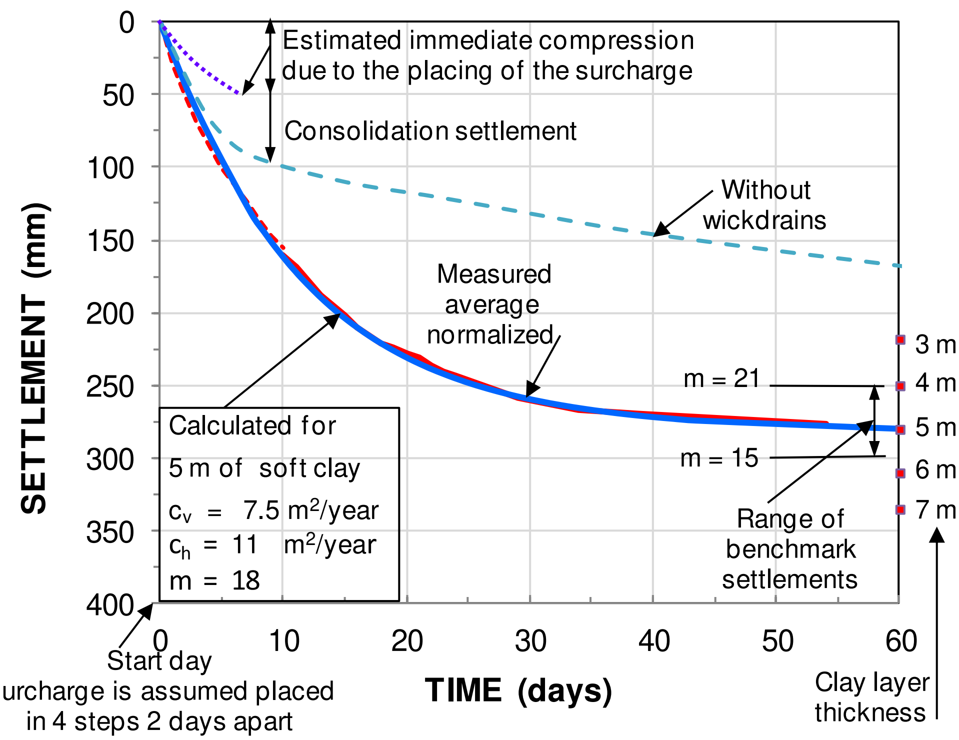

Figure 4. Average measured and calculated settlements.

Considering that my data reduction is quite different to that of the authors, my back-calculated c_h-coefficient (11m^2/year) agrees well with the authors' laboratory-established value (14m^2/year). The difference could be taken to represent the effect of a smear zone. However, considering all the uncertainties involved, I believe the agreement to be entirely fortuitous.

I must emphasize that without the support of data from measurement of areas with different spacing of drains, drains of different sizes, and different surcharge level, conclusion regarding the smear effect cannot be drawn. I do recognize, of course, that the authors have presented the results from an engineering project and the study was not a specifically designed research project, but limited to the details recorded for the project.

The authors have indicated the final settlement is 100% degree of consolidation. This is not correct; it is 100% of the measured settlement. At Day 50 (or 40 in the authors count), about 85 to 90% of the consolidation had occurred. The remaining amount, small as it is, will take considerable time to develop.

A final point is that I am surprised that the surcharge was designed to correspond to the exact load expected from the containers to be stored at the site. Sooner or later, the site will have to be upgraded, say, for reasons of adjusting to the final portion of the consolidation settlement, about 40 mm and secondary compression of about the same magnitude, which means that additional fill will be placed. This fill will start a new consolidation. If the surcharge had included an extra, say, 0.5 m of fill, such maintenance would have resulted in stress changes within the preconsolidation range established by the preloading and practically eliminated any future settlement due to the maintenance.

REFERENCES

Asaoka, A., (1978). "Observational procedure of settlement prediction." Soils and Foundations, the Japanese Geotechnical Society, JGS, 18(4) 67-101.

Barron, R.R., (1947). "Consolidation of fine-grained soils by drain wells." Proceedings of the ASCE 73(6) In Transactions of the ASCE 1948 (113) 718-742.

Fellenius B.H., (1977). "The equivalent sand drain diameter of the bandshaped drain." Discussion. Proc. 9th ICSMFE, Tokyo, July 10-15, Vol. 3, p. 395-396.

Goudreault, P.A. and Fellenius, B.H., (2011). "UniSettle Version 4 tutorial with background and analysis examples." UniSoft Ltd., Ottawa. [www.UniSoftLtd.com]. 85 p

Hansbo, S., (1960). "Consolidation of clay with special reference to influence of vertical sand drains." Swedish Geotechnical Institute, Stockholm, Proceedings No. 18, 160 p.

Hansbo, S., (1979). "Consolidation of clay by band-shaped prefabricated drains." Ground Engng, London, 12(5) 16-25.

Kjellman, W., (1948). "Accelerating consolidation of fine-grained soils by means of cardboard wicks." Proc. 2nd ICSMFE, Rotterdam, Vol. 2, pp. 302-305.

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