Settlement of a Pile Group — A Back Calculation of a Case History

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It is commonly thought—presumed—that when piles are installed to an adequate factor-of-safety on capacity, settlement issues are taken care of automatically. This is not necessarily so, as shown in the following case history of a settling foundation for a furnace bank. A back-analysis of the case data illustrates that settlement analysis of the piled foundation could have been carried out as a part of the original design applying simple, well-established methods, and the observed settlement need not have surprised the designers of the foundation.

The case history is quoted from a paper by Golder and Osler (1968)[1] presenting a case history of twelve years of settlement of a bank of five furnaces at the QIT plant in Sorel, Quebec. Each furnace has an 16 m by 10 m footprint and is supported on a group of thirty-two 0.6 m diameter expanded-base piles (Franki piles) with 6 m embedment installed to a depth of 8.5 m and c/c of from 2.1 m and 3.2 m. The furnaces are placed at a depth of 1.5 m about 6 m apart over an about 16 m by 55 m area. The total furnace load is 21 MN/furnace, i.e., a load of 670 kN/pile and an average stress of 130 kPa over each 160-m^2 furnace footprint.

The soil profile consists of compact alluvial brown sand to a depth of 10.5 m, a 1.5 m thick interbedded layer of fine sand and soft clay, and compact to dense grey sand to 19 m depth. The sand is deposited on 5 m of sandy clay on a 40+ m thick layer of Champlain Sea clay (formerly called Leda clay). The groundwater table is assumed to lie at a depth of 4 m and the pore pressures distribution is assumed to be hydrostatically distributed. The paper reports results on laboratory tests available from four Champlain Sea clay samples obtained in a borehole at depths ranging from 14 m through 38 m located approximately 2,000 m away from the QIT site. Fig. 1 shows the results of one of these tests. The four tests indicate virgin Janbu modulus numbers ranging from about 5 through 9, a re-loading modulus number of about 90, and a preconsolidation stress margin of 30 kPa through 80 kPa. The values are in tolerable agreement with typical values for Champlain Sea clay, usually exhibiting Janbu virgin and re-loading modulus numbers of 7 and 60, respectively, and a preconsolidation margin of at least 30 kPa.

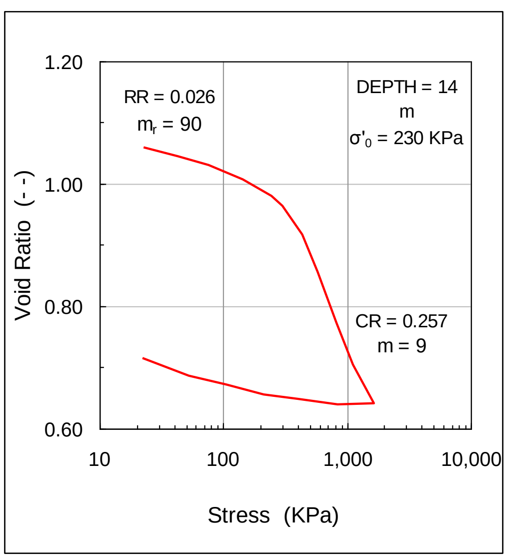

Fig. 1 Void ratio versus stress from consolidation test on sample from Champlain Sea clay

[1] Golder, H.Q. and Osler J.C., 1968. Settlement of a furnace foundation, Sorel, Quebec. Canadian Geotechnical Journal 5(1) 46-56.

The layout of one furnace pile group and the main soil profile is sketched in Fig. 2.

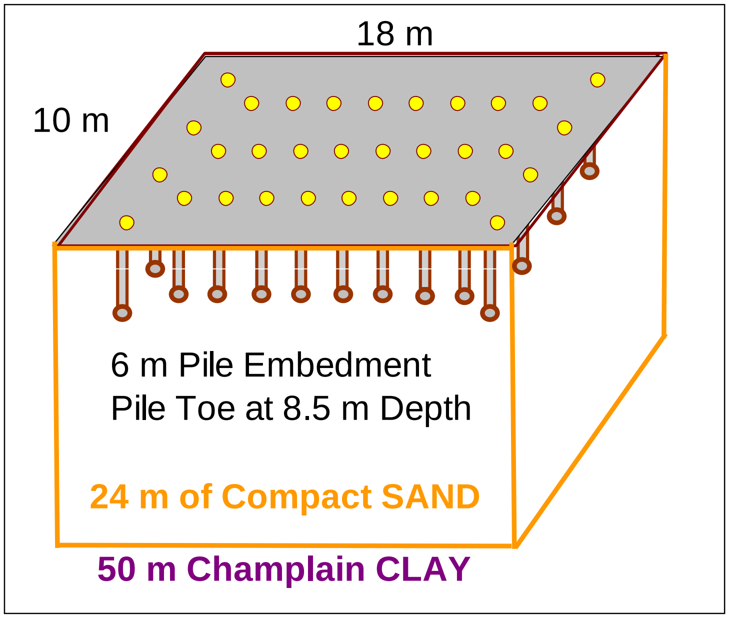

Fig. 2 Sketch of furnace pile group and soil profile

Figure 3 shows the load-movement curve of a static loading test performed on one of the piles to a maximum load of 1,800 kN, twice the working load. The load-movement curve of the test was essentially a straight line indicating that the pile capacity is much larger than the maximum load applied in the test and consisting mostly of toe resistance. The measured movement of the piles for a load equal to the working load was about 1 mm. The load-movement of the pile toe for the applied load is considered small, a few millimetre only. The test results were used to predict that the settlement of the furnace under full load would amount to 10 mm.

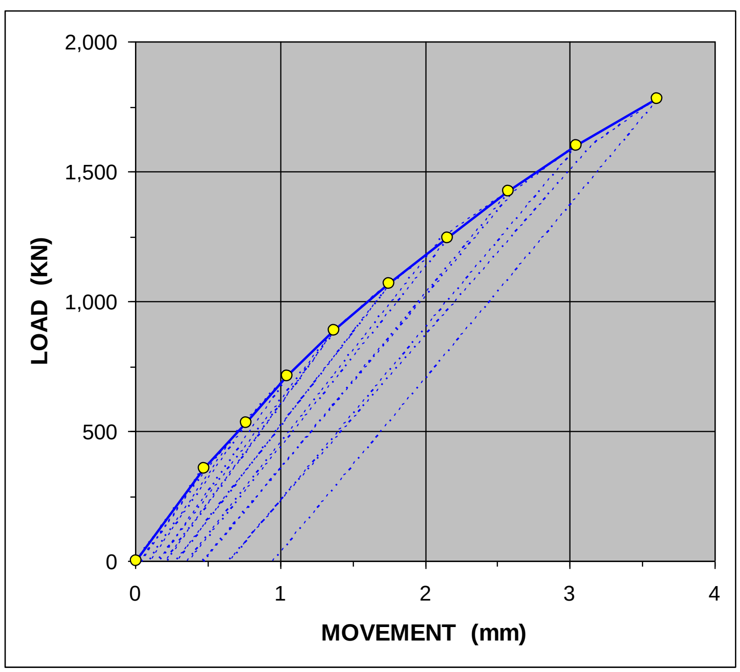

Fig. 3 Load-movement curves from the static loading test

The furnaces were built in early 1951. Settlement of the furnaces was monitored until November 1965. Fig. 4 presents the layout in plan of the five furnaces and location of the settlement monitoring points. Fig. 5 presents settlements across a section through the furnaces measured from April 1951 (when all five furnaces were completed) through January 1962. The "zero" reading was taken earlier for Furnace #1 than for Furnace #2 through 5, that is, the amount of initial settlement included in the records is not the same for the bank of five furnaces.

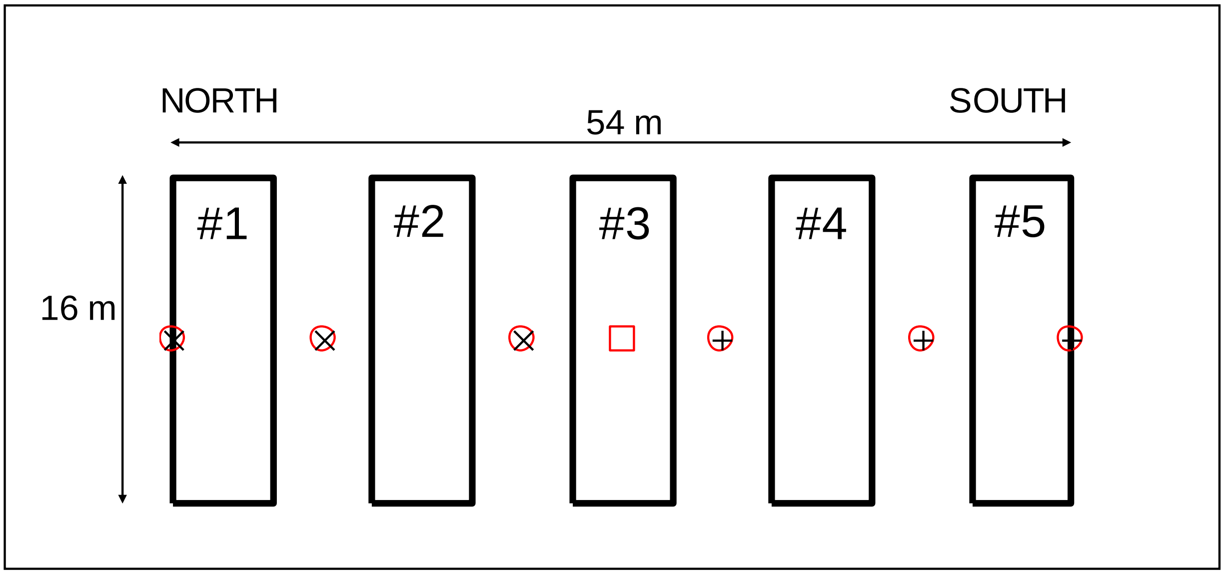

Fig. 4 Layout of furnaces and observation points

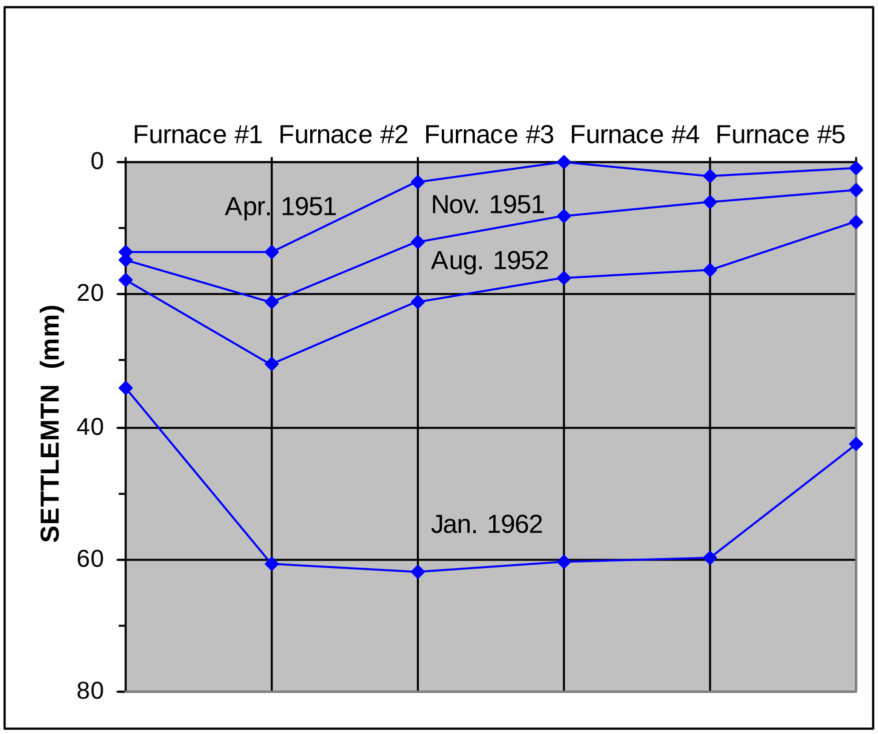

Fig. 5 Settlements from early 1951 through January 1962

Fig. 6 shows the settlements versus time with approximate trend lines superimposed. The dashed trend lines represent measurements at center of Furnaces #1 and #5 ("Side Furnaces") and measurements taken between Furnaces #2 and #3 and Furnaces #3 and #4, (the "Center Furnaces"). The trend lines imply that the consolidation is more or less completed after the twelve years. The small settlement occurring after January 1962 is due to secondary compression.

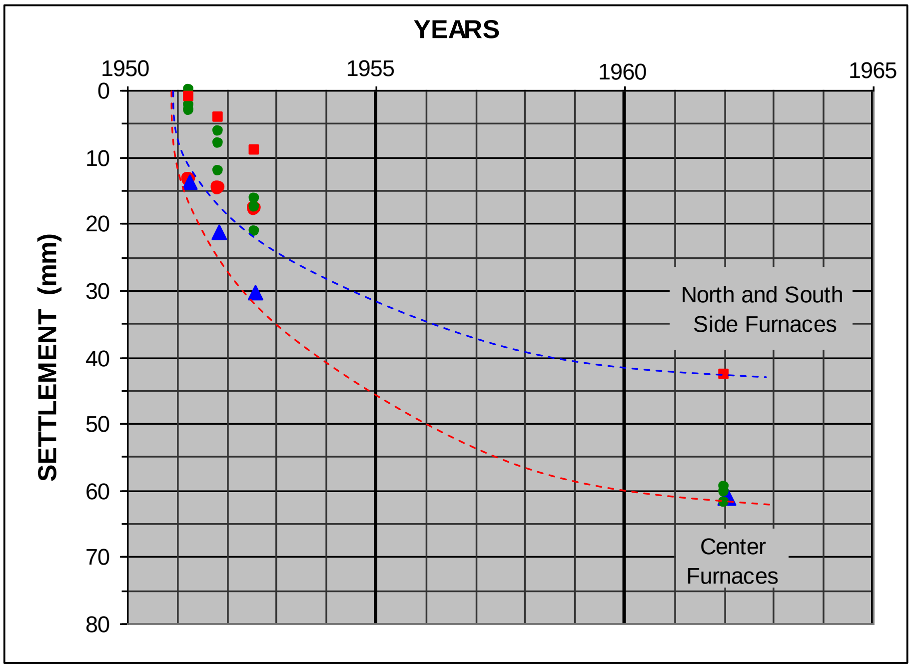

Fig. 6 Settlements plotted versus time

It is qualitatively obvious that the soil stresses due to the furnace loads will be the largest under the center furnace, Furnace #3, and be the smallest for the two end furnaces, Furnaces #1 and #5. The stress distributions can be determined numerically. Fig. 7 shows the Boussinesq stress distributions underneath each furnace as caused by the load on one furnace, Furnace #1, and calculated with the UniSettle program[2]. The stress distributions indicate that the load on one furnace has little effect beyond the depth of one furnace width, about 10 m. However, the stresses from all five furnaces accumulate and the settlement difference between the center and the edges of the furnace bank is not that large.

Figure 8 shows the calculated Boussinesq stress distribution below the outside edge of Furnaces #1 and #5 and below the center of Furnace #3. Note that for a preconsolidation margin of, say, 30 kPa, at the depth interval of 30 m through 40 m, the settlement caused by the stress below the center of Furnace #3 will result in significantly larger settlement as opposed to those from the stress below the outside edge of Furnaces #1 and #5, where the imposed stress is smaller than the preconsolidation margin.

[2] Fellenius, B.H. and Goudreault, P.A., 1996. UniSettle Users Manual, UniSoft Ltd., [www.UniSoftLtd.com], 76 p.

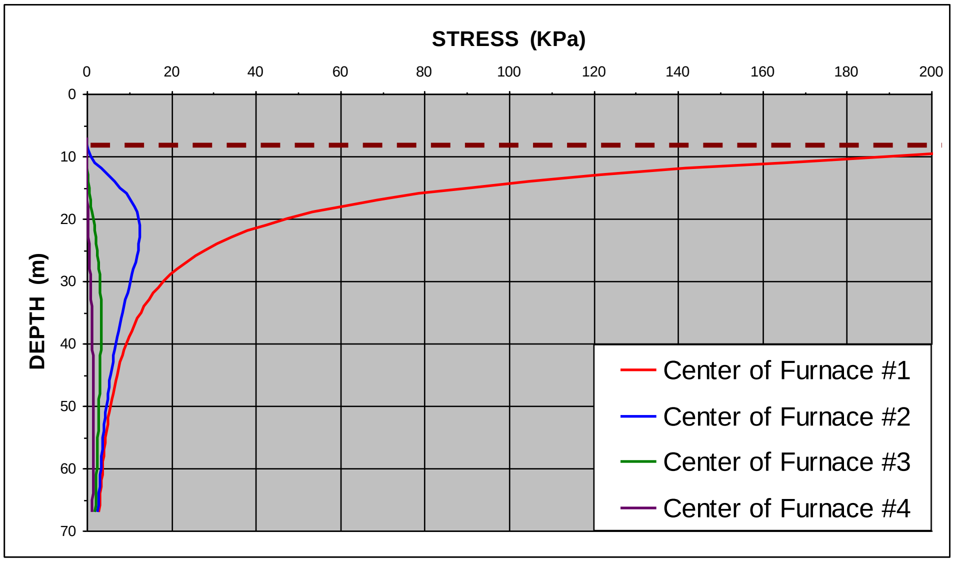

Fig. 7 Boussinesq stress distribution for the stress from Furnace #1 under its own center and under the center of Furnaces #2, #3, and #4

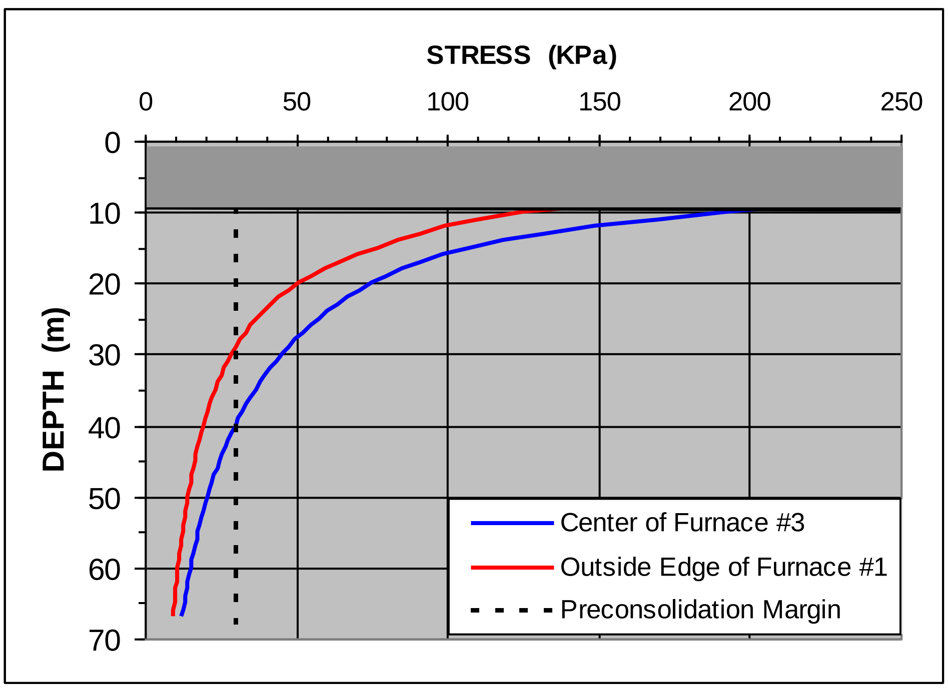

Fig. 8 Boussinesq stress distribution below the outside edge of Furnace #1 and the center of Furnace #3

The imposed stress from the furnaces resulted in settlements as governed by the soil compressibility and preconsolidation margin. Reasonably, during the first about half a year, all the initial settlement and most the settlement in the dominantly sand soils above the depth of 24 m will have developed, and the thereafter occurring settlement is from consolidation of the clay soils below this depth. The observed settlement after November 1951 measured at the center of the furnace bank, Furnace #3, is matched to a calculation using input that is typical for the soils at the site. As mentioned, most of the settlement in the sand soils must have occurred before that time. Therefore, the key input to the calculations consists of the input representing the two layers of clay between the depths of 24 m and 29 m and below 29 m, respectively, i.e., virgin and re-loading modulus numbers and preconsolidation margin. The three values mentioned above as typical for the Champlain Sea clay is used as input to the calculations. The firm silty clay above the Champlain Sea clay layer is less compressible and, moreover, most of its consolidation will have occurred within the first half year. For the silty clay, representative values of virgin and re-loading modulus numbers are considered to be 15 and 100, respectively, coupled with a preconsolidation margin of 30 kPa. About 50 % consolidation can be assumed to have occurred in the silty clay during the first half a year, which can be represented by a modulus number of 30 as input to the UniSettle calculations. The analysis has also to include stress from site preparation surface fill, typically 0.5 m thick. The input for the sand and the extent of the surface fill is adjusted to fit the calculated settlement to the value of about 60 mm observed at the center of the furnace bank. Of course, the same settlement amount can be obtained for quite a variation of selected input parameters. However, the chosen input is adequate for the purpose of demonstrating the analysis of the foundation stresses and settlements, as well as to show how modern analytical tools (computers), which were not available in 1968, can be applied to the case history reported in the paper.

The results of the settlement calculations are shown in Fig. 9 together with the measured settlement. The settlement calculated for the for the two outside pairs of values employ the same soil input as used for the center point pair. Fig. 7 does not include the initial settlement occurring before April 1951, the first about half year of records.

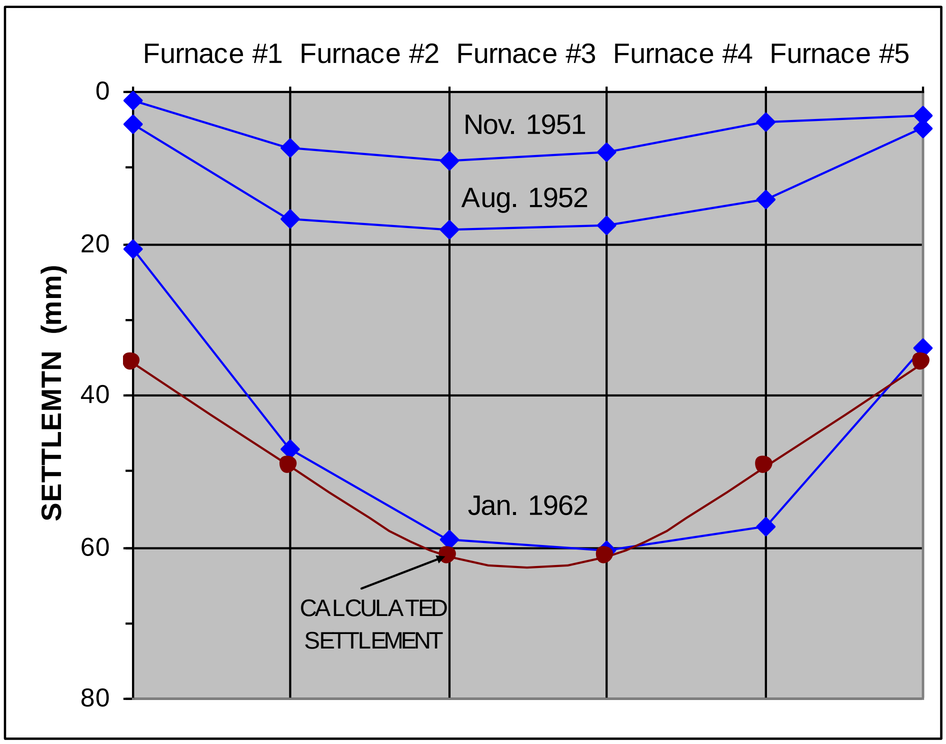

Fig. 9 Calculated and measured settlement

The calculations can also be used to determine the vertical distribution of settlement at different location over the foundations. Fig. 8 shows the distributions calculated for the outside edges and the center of the furnace bank.

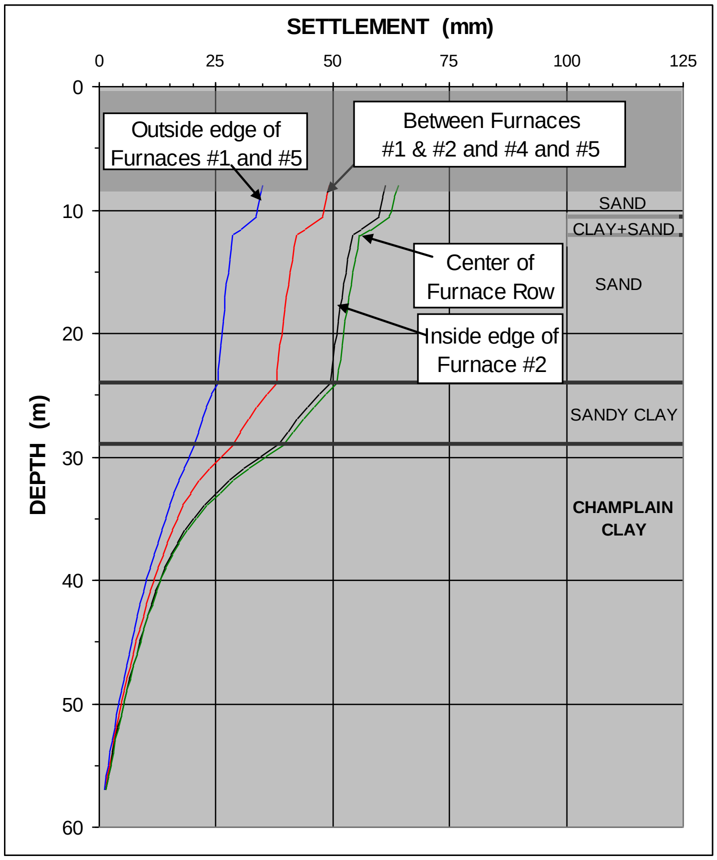

Fig. 8 Vertical distribution of settlement calculated at the edge and center of the furnace bank

In 1968, Furnace #1 was demolished and a new furnace was built re-using the old piles. The new furnace was heavier than the old, 45 MN as opposed to 24 MN, which required adding new piles to the existing pile group (installed to an embedment depth of 11 m). The new piles were placed in two rows along the long side of the old foundation effectively increasing the width from 6 m to about 10 m. The new foundation stress is estimated to 280 kPa. It was assumed that the piled foundation would act as a unit.

The demolition of the superstructure of the existing furnace was predicted to result in an unloading of 77% of the weight, i.e., by a stress unload of 162 kPa. The paper indicates that the unloading would result in an estimated 3 mm heave of the existing foundation. Attempts were made to measure the heave, but the measurements were interrupted and became very approximate. The paper indicates that the observed heave was approximately within an "*order of magnitude of the predicted value*". UniSettle calculates the heave using the mentioned input of re-loading modulus values for the soil layers. The calculation results in heave values at the center of Furnaces #1, #3, and #5 of about 14 mm, 3 mm and 1 mm, respectively.

The paper mentions that the estimated settlement for the new furnaces was an additional 170 mm for the center of the New Furnace #1, but does not report any measurements of the actual settlement. Using the same soil input as before as well as the footprint and stress of new furnace, the calculated additional settlements at the center of New Furnaces #1, and existing Furnaces #3, and #5 are about 35 mm, and 8 mm and 2 mm, respectively.

The available soil information is sketchy and the calculations have been fitted to the settlement measured at the center of the furnace bank. Moreover, the input parameters used for each sub layer of soil consist of three values (virgin and re-loading modulus numbers and the preconsolidation margin) and the very same settlement value could have been obtained using different values of these parameters. The magnitude and extent of any surcharge fill is not known. Therefore, the agreement between the calculated stresses and settlements may or may not indicate that the input values are correct. However, the example shows that having access to reliable information, calculations using basic and well-established methods will provide representative distributions of stresses and settlement over a site as caused by variety of load configurations.

The example also demonstrates that load-movement results of a static loading test are unreliable data for predicting settlement of a piled foundation. Moreover, even if a piled foundation has adequate capacity (or more than adequate in this case) it can still be subject to excessive settlement. Settlement analysis of piled foundations is omitted at one's peril!

Although a hindsight conclusion, it is obvious that the piling serves as a ground improvement method, densifying the sand. The same effect could have been obtained constructing the foundation as a piled pad. That is, not connecting the piles to the raft (mat), but separating the piles from the raft by a compacted granular layer. It is also probable that the adding of piles, and longer piles, for the New Furnace was redundant.