A NEW, INNOVATIVE CONSOLIDATION SYSTEM BASED ON THE PROVEN CONCEPT OF VACUUM CONSOLIDATION

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ABSTRACT

Many of the large cities in the world are located in coastal plains or deltaic areas, near rivers and other waterways. Although these locations may be favorable from an economic point of view, they are often dominated by poor subsoil conditions. Highly compressible fine grained sediments such as clays, silts and peat, generally have low shear strengths and cause settlement and stability problems when loaded by structures like roads, railways, dikes, fills, etc.

Economic incentives nowadays stimulate trends like the reduction of the return-on-investment period and, therefore, the construction time, but encourage also seemingly conflicting construction requirements reducing the maintenance during the operational lifetime of the structures. In addition, growing public awareness in a more and more congested environment urges the construction risks to be reduced.

These developments combined with shifting responsibilities as a result of new contract forms (i.e. turn key, etc.) have stimulated the development of new techniques to either accelerate the consolidation process or reduce the absolute settlements in compressible soils without running into risks of failures or long-term maintenance.

Systems to accelerate the consolidation process are all based on 2 principles:

- Reduction of the length of the drainage path of the pore water and/or the application of a surcharge. A surcharge usually consists of sand, but may also be the atmospheric pressure as result of vacuum consolidation.
- Reduction or elimination of settlements is generally achieved by either reducing the compressibility of the cohesive strata by introducing binding agents in the ground (block stabilization) or concentrating the bearing loads onto stiff elements like piles or columns that transfer these loads to underlying, more competent strata.

Some techniques combine the acceleration of the consolidation with the use of stiff elements. Generally the techniques that reduce or eliminate settlements will be expensive in comparison to those that accelerate consolidation.

This paper will focus on a new system called BeauDrain that combines the proven technique of vertical and horizontal drainage and vacuum consolidation with an innovative installation procedure. The soil mechanical principles, the system itself, the design and monitoring and the results of a test site, known as the test site Zevenhuizen, will be discussed. Finally the performance of the system during the construction of the RW 11, a highway between Alphen a/d Rijn and Bodegraven in the Netherlands, will be reviewed by presenting and interpreting monitoring data.

KEY WORDS

VACUUM CONSOLIDATION / SOIL IMPROVINGTECHNIQUES / RISK REDUCTION.

1. DESIGN OF AN EMBANKMENT

A design of an embankment on soft, compressible soils generally needs to meet criteria like:

- Functional requirements specified in terms of settlement (long term settlements, differential settlements);
- Stability requirements during and after construction, usually expressed in terms of minimum safety factors;
- A limited construction period.

Settlements include primary and secondary settlements. Primary settlements are controlled by consolidation. Settlements after construction can be reduced by surcharging and accelerating the consolidation process during construction.
Stability is related to the in-situ strength properties of the soil and the degree of consolidation achieved after application of the load.
Therefore, a design of an embankment shall specify a surcharge and a loading rate.
Moreover, to ensure stability it will be required to match the loading rate and the rate of consolidation by installing an appropriate drainage system.

The degree of consolidation as a function of the time may be expressed as:

$$U = \sqrt[6]{\frac{T_v{}^3}{T_v{}^3 + 0.5}} \tag{1}$$

In which: U = degree of consolidation [-]
T_v = vertical time factor [-]

Equation (2) demonstrates the influence of the length of the drainage path on the vertical time factor and, hence, on the consolidation period. Reduction of the length of the drainage path, usually equal to the thickness (or ½ H in case of two-sided drainage), can be achieved by installing vertical drains or other draining elements.

$$T_v = \frac{c_v \cdot t}{H^2} \tag{2}$$

In which: c_v = vertical consolidation coefficient [m^2/s]
H = length of drainage path of the pore water [m]
t = consolidation time [s]

As follows from the formulae above, applying a surcharge does not accelerate the consolidation process, but results in a larger settlement in the same consolidation period. This implies that the required settlement can be reached in a shorter period, after which the surcharge has to be removed to avoid more settlement than strictly required. Figure 1 depicts the time-settlement curves of normal consolidation, consolidation with only vertical drains (reduction of the length of the drainage path) and surcharging in combination with vertical drains.

According to Mesri (1975), the undrained shear strength depends on the effective stress as follows:

$$s_u = f * \left(s\text{`} + U \cdot \Delta s\right) \tag{3}$$

In which: s_u = undrained shear strength [kPa]
s' = effective stress [kPa]
Δs = increase total stress [kPa]
f = factor equal to 0.22

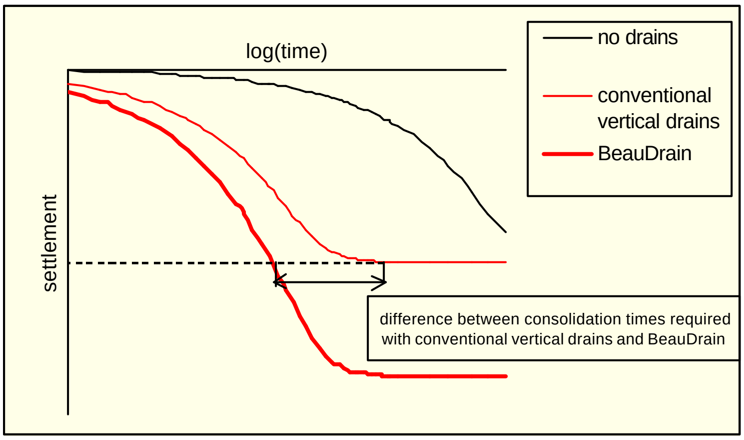

Figure 1 - Consolidation periods of various methods

In terms of effective stress the same relation may be expressed as:

$$\tau = c` + (\sigma`_{init} + U \cdot \Delta\sigma) \cdot \tan\phi` \qquad (4)$$

In which: t = shear strength [kPa]
c` = cohesion [kPa]
$\phi`$ = angle of internal friction [°]

2. VACUUM CONSOLIDATION

In its most simple form, the method of vacuum consolidation comprises a system of vertical drains and a drainage layer (usually sand) at the top, sealed from the atmosphere by a geomembrane placed at the surface. Horizontal drains installed in the drainage layer, and connected to pumps in combination with the vertical drains, remove the pore water from the compressible strata and reduce the atmospheric pressure in these layers.

The increase of the effective stress for a conventional surcharge at time t_1 can be written according to equation (5). When combining the same surcharge with vacuum consolidation the increase in effective stress can be calculated using equation (6).

$$\Delta\sigma`(t_1) = U(t_1) \cdot \Delta\sigma_s \qquad (5)$$

$$\Delta\sigma`(t_1) = U(t_1) \cdot \Delta\sigma_s + U(t_1) \cdot p_v = U_{eq}(t_1) \cdot \Delta\sigma_s \qquad (6)$$

In which: $U(t_1)$ = degree of consolidation at t_1
$\Delta\sigma_S$ = surcharge
p_V = vacuum pressure
$U_{eq}(t_1)$ = equivalent degree of consolidation at t_1

As $U_{eq}(t_1)$ will exceed $U(t_1)$ for all $t>0$ the increase of the effective stress for a combination of surcharge and vacuum consolidation will always be more than for a situation with a surcharge only.

Unlike physical loads, the vacuum pressure does not introduce shear stresses in the subsoil as a result of its isotropic character and will, therefore, not cause instabilities. The resulting settlements due to the vacuum loading are also isotropic. The effect of the vacuum consolidation on the loading rate is demonstrated in Figure 2.

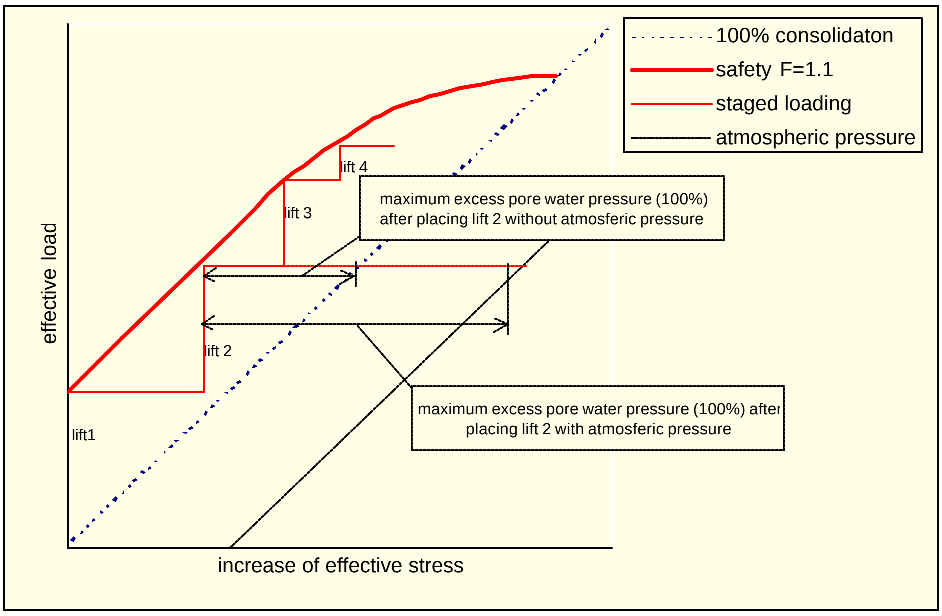

Figure 2 - The relation between the applied (effective) weight of the embankment and the resulting increase of the effective stress

This figure presents the relation between the effective weight of an embankment and the increase of the effective stress during construction. The curved line, constructed from a number of stability calculations, represents the maximum loading line corresponding with a required safety factor (SF = 1.1). The staged loading line depicts 4 stages of an arbitrary loading path including intervening consolidation phases. The 100% consolidation line presents the situation of the effective load equaling the increase of effective stress. The vacuum pressure line runs parallel to the 100% consolidation line at a horizontal distance equal to the vacuum pressure. The maximum excess pore water pressure after placing a lift can be determined by taking the difference between the staged loading line and the 100% consolidation line in case no vacuum is applied. In the case of vacuum consolidation the excess pore water pressures will be represented by the difference between the staged loading line and the vacuum pressure line. As the rate of consolidation depends only on c_v and the drainage length dissipation of excess pore water pressures in both cases will require the same time. This implies that the rate of increase of effective stress during vacuum consolidation with surcharge will be more than with just vertical drains and a surcharge. Figure 2 shows that this effect will allow for a higher loading rate.

3. ASAOKA METHOD

With the reduction of the consolidation period, it becomes increasingly important to monitor the development of the settlements with time and to accurately predict the final settlement in an early stage of the consolidation process as the time for corrective measures is generally limited.
Asaoka [1] has proposed a simple method to predict the final settlement based on settlement observations at fixed time intervals. By plotting consecutive readings z(t) against z(t+1) a line will be obtained which, over a large interval, can be represented by the linear function:

$$z_{t+1} = \beta \cdot z_t + A \tag{7}$$

In which: ß = slope of the linear section of the best fit [-]
A = intersection of the extrapolated section of the linear fit with the Y-axis

A few so-called Asaoka lines, representing various loading stages of a reclamation project, have been depicted in Figure 3.

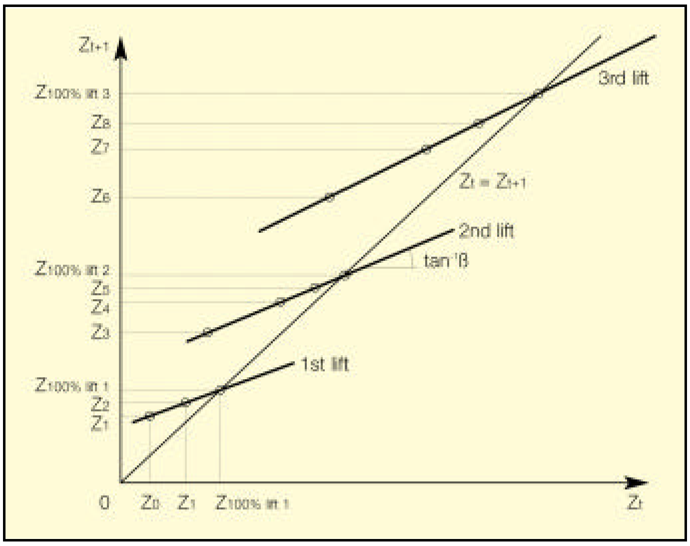

Figure 3 - Asaoka lines

The intersection point of the extrapolated section of this straight line and the line z(t)=z(t+1) will define the total final settlement at the moment full consolidation has been reached (see equation (8)).

$$z_{100\%} = \frac{A}{1-\beta} \tag{8}$$

The tangent of the plotted line can be related to the equivalent consolidation coefficient c_{eq} (consolidation coefficient accounting for the joint effect of the horizontal and vertical drainage of pore water) by applying the following formula:

$$c_{eq} = \frac{-5 \cdot H^2 \cdot \ln \beta}{12 \cdot \Delta t} \tag{9}$$

In which: H = length of drainage path [m]
?t = time interval [s]

As demonstrated by Luger et al. (1999), ref. [2], reliable predictions with this method can only be achieved once the degree of consolidation has exceeded approx. 40%. Moreover, as the predicted final settlement also includes secondary settlement continuing linearly with the logarithm of the time, plotted results tend to deviate from a straight line when the measured settlements become small (i.e. when the degree of consolidation becomes high). To improve the graphical resolution, Luger et al. [2] have suggested to plot the difference between z(t+1) and z(t) against z(t). In this case, the final settlement is represented by the intersection point of the extrapolated linear fit of the data points with the X-axis (z(t+1) = z(t)).

4. BEAUDRAIN SYSTEM

The BeauDrain system is a recently developed vacuum consolidation technique with an innovative installation procedure. Through a specially designed plough that is pulled by a hydraulic crane, prefabricated vertical (wick) drains are installed and cut at predefined depths below ground level. While the plough is moving a horizontal collection drain is placed at a depth of approx. 3 m below ground surface and is connected to the vertical drain. Before it leaves the plough, the horizontal drain is also covered by an impervious geomembrane in order to ensure a proper sealing between the horizontal drain and the atmospheric conditions. The whole system, which is usually referred to as a drainage curtain, consists of a row of vertical drains, a horizontal drain and seal. It is placed in a single pass of the plough. Figure 4 illustrates the installation of the system. After passage of the plough the compressible soil closes in on itself above the horizontal drain creating a natural seal additional to the geomembrane. The total system consists of a number of drainage curtains connected to vacuum pumps. The crane with plough is depicted in Figures 5 and 6.

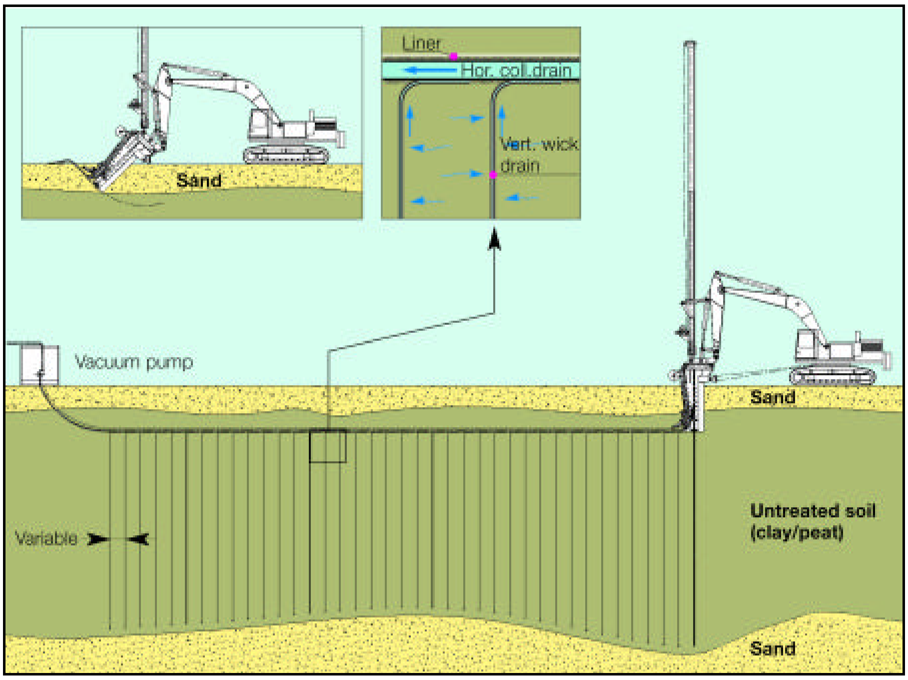

Figure 4 - Installation BeauDrain system

Figure 5 and 6 - BeauDrain machine with a detail of the plough

The vacuum measured at the pumps generally varies between 80 kPa and 90 kPa (0.8 – 0.9 bar). Depending on the height difference between the pump and the horizontal drain, this usually results in a reduced pressure of approx. 50 - 60 kPa in the horizontal drain. This vacuum pressure of 50 - 60 kPa, corresponding to a surcharge equivalent of approx. 3.5 m (dry) sand, acts on the compressible strata as a load. Figure 7 clearly shows the increase of the effective stress as a result of the reduced atmospheric pressure in the soil mass. The net effect of this is an additional surcharge, which will ensure an early attainment of the required settlement, and an increased shear strength which will favour the stability (accelerated loading schemes, steeper slopes in areas with limited space).

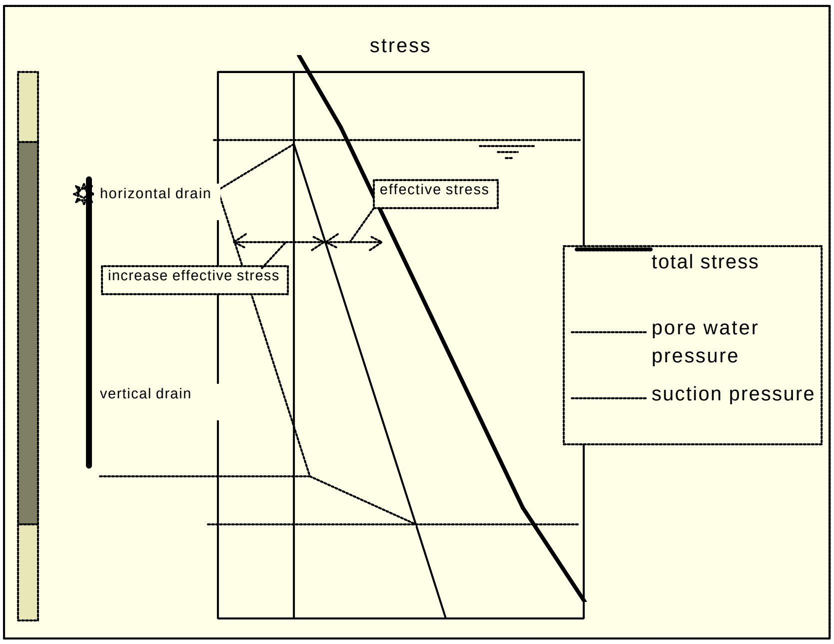

Figure 7 - Effective stress increase as result of suction pressure

5. TEST SITE ZEVENHUIZEN

Figure 8 shows settlement readings gathered in 2 adjacent test sections of the test site Zevenhuizen, one equipped with the conventional vertical wick drains, the other with the newly developed vacuum consolidation system. In both sections the initial sand surcharge equalled 1.5 m. After 100 days the thickness of this sand layer in both areas was increased to 3 m. Figure 9 gives an overview of the test area. The transition between the settled BeauDrain section (left) and the area with conventional vertical drains (right) is clearly visible. Although the type, length and spacing of the vertical drains and the thickness of the sand surcharges were identical in both sections, it is clear that the vacuum created by the pumping has accelerated the consolidation considerably. In each section a borehole was made and samples recovered. Laboratory tests included (undrained) vane tests, determination of water contents, volumetric weights and oedometer tests.

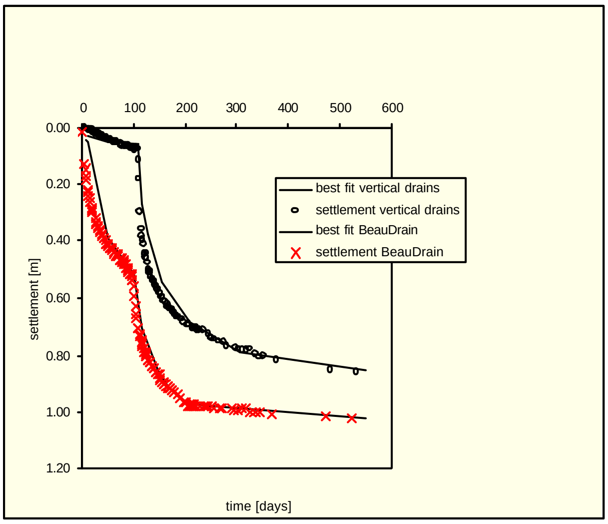

Figure 8 - Settlement readings Zevenhuizen and best fit

As can be seen from Figure 8 the settlement rate in the BeauDrain section exceeded that of the section with only vertical drains. The pumps were stopped after 206 days. The relief of the atmospheric surcharge in the section with vacuum consolidation is clearly marked by the sudden reduction of the settlement rate. From a back analysis it was concluded that approx. 50% of the total atmospheric pressure, i.e. 50 kPa had been mobilised as an additional surcharge. The in-situ consolidation coefficient was calculated with the Asaoka method.

Figure 9 - Overview test site Zevenhuizen with conventional vertical drains on the right, BeauDrain on the left

6. EMBANKMENTS RW11

As part of the construction of the RW11, a new highway between Alphen a/d Rijn and Bodegraven in the western part of the Netherlands, an embankment of a fly-over had to be raised in short time to a level of 9 m above existing ground level. The stratigraphy in this area known for its adverse subsoil conditions is dominated by sequences of soft to very soft, highly compressible peat and clay covering the Pleistocene sands at a depth of 8 – 9 m below ground level. These soft to very soft cohesive strata had typical undrained shear strengths of 5 - 10 kPa, bulk unit weights of approx. 11 kN/m^3 (peat) and 15 kN/m^3 (clay). Predicted settlements ranged between 2 – 3 m. The embankment was located immediately next to a 10 m wide canal, which could cause stability problems. To avoid excessive bending moments in the piles of the abutments of the fly-over settlements after driving the piles had to be limited to 0.20 m in 30 years.
To enable the construction of this embankment within the available time frame, the newly developed vacuum consolidation system was installed.

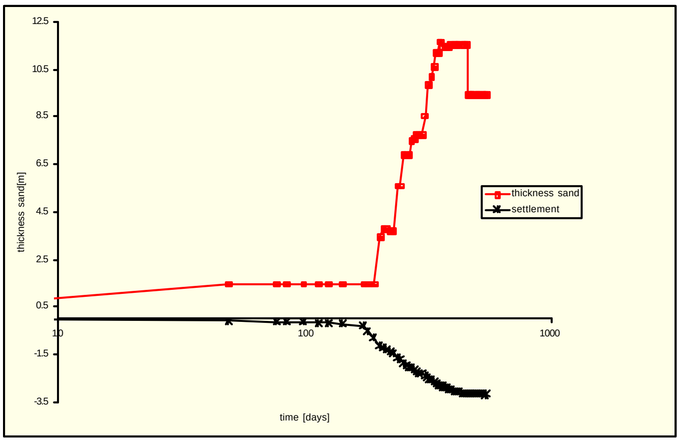

Figure 10 - Thickness sand and corresponding settlement as function of time

After placing a working platform of 1.0 – 1.5 m of sand the vertical drains were installed at a 1 m spacing. The distance between the curtains was also 1 m. Settlement beacons were used to record the settlements, while piezometers were installed to measure the pore water pressures. Figure 10 presents a typical record of a settlement beacon showing both the settlement and the thickness of the sand placed as a function of the time. The in-situ coefficient of consolidation was determined with the method of Asaoka. Based on a back analysis of the settlement readings predictions were made of the long term settlements.

These predictions were then used to determine the moment that the remaining settlements would meet the settlement requirements and the pumps could be switched off.
With the new vacuum consolidation system operational it was possible to raise the embankment within 120 days and without stability problems to a level of approx. 9 m above original ground level causing at the same time settlements ranging between 2 – 3 m.

Immediately adjacent to the location of this high embankment the foundations of the highway itself had to be consolidated in a short period. The BeauDrain system was installed in this area as well, but with the intention to accelerate the settlement process of this low embankment rather than improving the stability.
A back analysis has been made to evaluate the effective suction pressure of the vacuum consolidation system. The results are presented in the format of an (applied effective) stress-strain curve, generally used to depict the results of an oedometer test. The calculation of the effective applied load from the weight of the sand and the surcharge is determined with the consolidation coefficient from the Asaoka analysis. Adjacent to this low-lying section with vacuum consolidation conventional vertical drains were installed in an area with approximately the same loading history and similar drain spacing. Figure 11 shows the stress-strain curves determined for settlement plate in both areas and best fit of the BeauDrain section. This fit includes an atmospheric surcharge of 50 kPa.

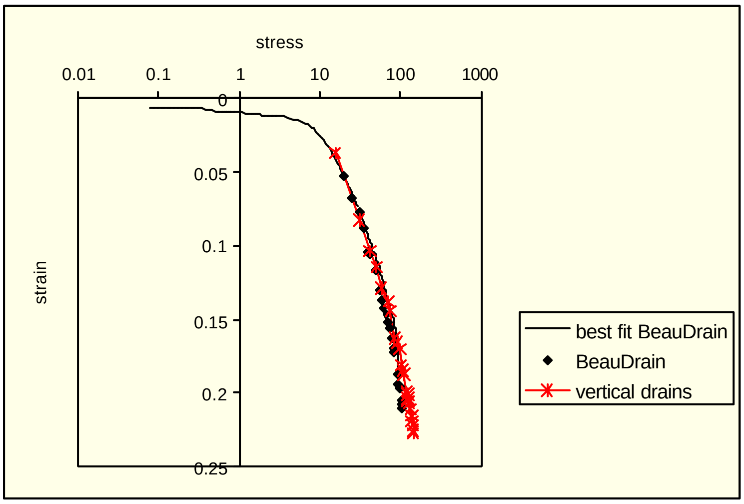

Figure 11 - Stress-strain curves of the sections with conventional drains and vacuum consolidation system and the best fit for vacuum consolidation system (including 50 kPa vacuum pressure)

7. CONCLUSIONS

The BeauDrain system combines proven techniques of vertical and horizontal drainage and vacuum consolidation with an innovative installation procedure.

Back calculation of the test site Zevenhuizen and the sections at RW11 project indicate that a surcharge of approx. 50 – 60 kPa can be mobilised by pumping. The isotropic nature of this load causes an increase of the effective stress without raising the shear stress level and reducing horizontal deformations during loading. This will result in a rise of the shear strength of the subsoil allowing for substantial higher loading rates without loss of stability or, alternatively, steeper slopes reducing the footprint of a construction. In particular for embankments of limited height, acceleration of the consolidation process and reduction of long term settlements may be achieved without large surcharges.

The Asaoka method proves to be a simple, powerful and reasonably accurate tool to predict the consolidation factor and the final settlement in a relatively early stage of consolidation.

8. REFERENCES

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