Performance of instrumentation under vacuum consolidation and vacuum consolidation and heating

Desempeño de una instrumentación para consolidación a vacío y a vacío combinado con calentamiento

Maria Esther Soares Marques
COPPE/UFRJ
Serge Leroueil
Université Laval
Márcio de Souza S. Almeida
COPPE/UFRJ

Abstract

Two trial embankments were built in order to study the behavior of a clay deposit under vacuum consolidation and vacuum consolidation associated with heating. Laboratory and in situ *tests were carried out prior to field consolidation. Special instrumentation was installed at the embankments and the vacuum consolidation was carried out during five months. The paper presents the description of the clay deposit with some laboratory and field tests results and discusses the instrumentation behavior and performance under these singular surcharge and temperature variation.*

Resumen

Dos rellenos experimentales fueron construidos con el fin de estudiar el comportamiento de un depósito arcilloso sometido a consolidación a vacío y a vacío casado con calentamiento. Pruebas de campo y de laboratorio fueron ejecutadas anteriormente a la consolidación in situ. Se estableció una instrumentación especial y el vacío ha sido aplicado por cinco meses. El contenido del artículo trata de describir un relleno arcilloso, acompañado de algunos de sus resultados de pruebas de campo y de laboratorio. Discutiese además sobre el comportamiento de la instrumentación y su desarrollo para este tipo especial de carga y bajo la variación de temperatura.

1 INTRODUCTION

Due to stability considerations, embankments over clayey deposits are sometimes built in several stages or with lighter materials, associated or not with vertical drains, depending on the construction schedule. With vacuum consolidation, the equivalent stress of a 4.5m conventional pre-loading fill can be applied to the clayey deposit in four to six months, as a function of the horizontal coefficient of consolidation of the soil and the vertical drains spacing. The increase in vertical effective stress is due to the decrease in pore pressure, so the vacuum consolidation can be applied in one single step, even on very soft soils.

Although the vacuum consolidation is not a well-known technique in America, it has been successfully used in different parts of the world (Choa 1989, Cognon et al. 1994, Jacob et al. 1994, Magnan 1994, Qian et al. 1992, Shang et al. 1998, Van Impe et al. 2001, Dong et al. 2001). In order to study the vacuum consolidation technique and heating, applied over a typical eastern Canadian clay deposit, two trial embankments 13m x 13m were executed approximately 30km North of Montreal, at Saint-Roch-de-l'Achigan (Fig. 1).

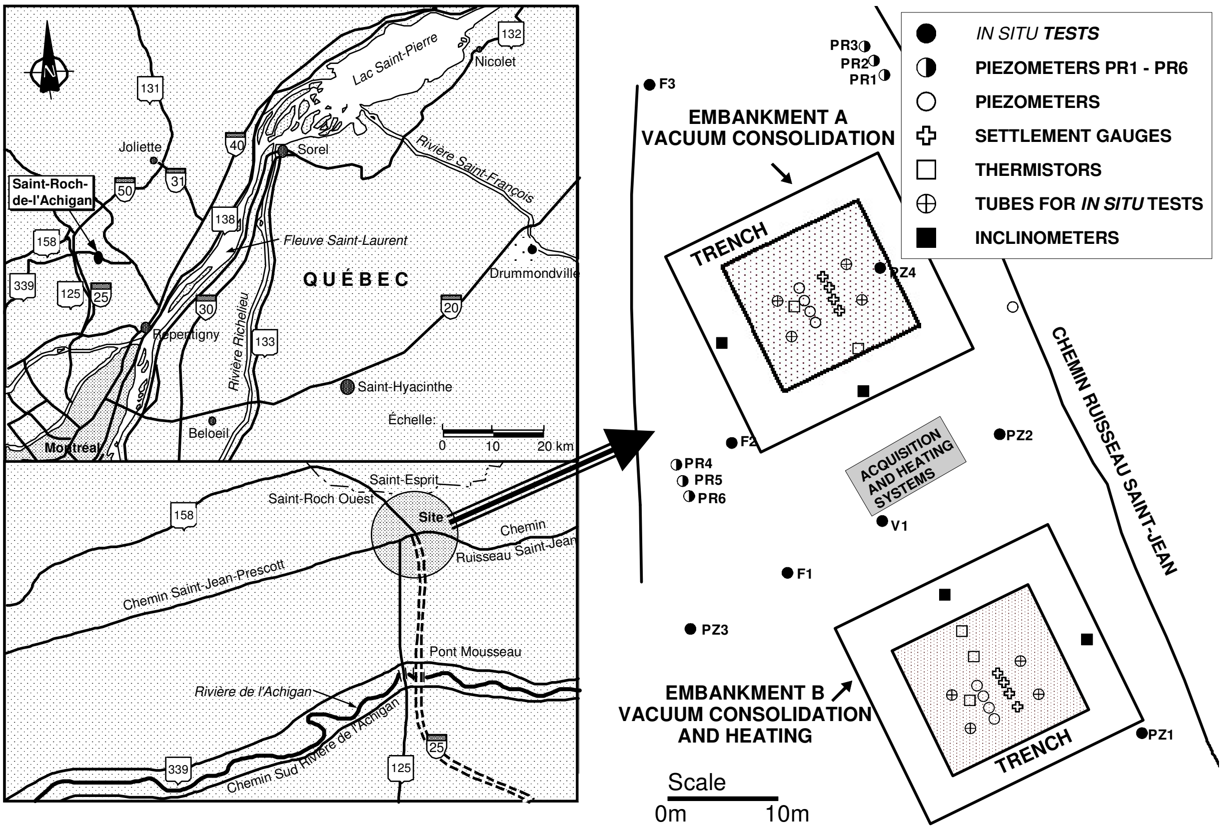

Figure 1- Localization and layout of Saint-Roch-de-l'Achigan site.

The deposit was subjected to vacuum consolidation (trial embankment A) and vacuum consolidation and heating (trial embankment B), down to approximately 7.5m depth. The heating was applied for five months and the vacuum consolidation was carried out over five months.

The idea of *in situ* heating comes from the fact that permeability increases with temperature. It was also observed in consolidation tests, that the heating of a sample in the normally consolidated domain increases its deformation and strain-rate (Leroueil and Marques, 1996). There are a few studies on *in situ* heating (Miliziano, 1992; Bergenståhl et al., 1994; Edil & Fox, 1994; Moritz, 1995), and it was the first time that a vacuum consolidation pre-loading was installed in Canada and the first time that vacuum consolidation was associated with heating.

2 SITE CHARACTERIZATION

Prior to field consolidation, samplings with Laval sampler (F1 to F3); vane test (V1); piezocone tests (PZ1 to PZ4) were carried out, and also six Casagrande piezometers were installed (PR1 to PR6), as shown in Fig. 1.

The clay deposit is quite homogeneous, composed of a 2.5m thick clay crust followed by a 10m slightly overconsolidated silty clay deposit (OCR between 1.8 and 2.4), overlying a glacial till, as shown in Fig. 2. Index and oedometer tests were performed with depth. Below the crust the initial permeability lies between 1.6 and 3.3 x 10^{-9} m/s and void ratio is about 2.3 to 2.5. The clay is very compressible, with a compression ratio CR = C_c / ($1+e_0$) between 0.59 and 1.36, a range where clay behaviour is significantly influenced by viscous phenomena during primary consolidation (Leroueil, 1996), as observed from laboratory tests carried out on this clay.

Laboratory tests, from 4.8 to 5.8m depth, were carried out in order to study the viscous phenomena under temperature and strain rate variation. Conventional and CRS oedometer tests, CIU and CAU triaxial tests and special oedometer tests, all under controlled temperature (Marques, 2001) were performed. From those tests it was observed that vertical yield stress typically varies by 1%/^{o}C from 5 to 40^{o}C and hydraulic conductivity increases 2.2 times when temperature increases from 10 to 50^{o}C, thus an important effect for field consolidation by heating.

3 VACUUM SITE CHARACTERISTICS

Preconsolidation by vacuum consists in applying vacuum on a deposit by pumping water from a grid of vertical and horizontal drains, decreasing pore pressures inside the deposit.

At the Saint-Roch-de-l'Achigan site, the 2" circular prefabricated vertical drains were installed with a spacing of 1.15m up to a depth of about 7.5m in the silty clay deposit, under the two trial embankments. Horizontal drains were placed in the 60cm thick sand layer, and they carried out the water pumped from inside the deposit towards the trenches. The trenches were excavated around the embankments to the water table. The vacuum PVC membrane was placed above the sand layer, and stretched to the bottom of the trench. After tests with the vacuum system the embankment was completed up to 2.3m. Difficulties related to the high depth of the water table on this site were described by Marques et al. (2000).

At embankment B, thin copper tubes (diameter = 3/8") were installed inside the vertical drains and hot water was pumped inside these tubes down to 7.3m depth, in a closed hydraulic system, independent of the vacuum pumping system, as shown schematically in Fig. 3.

First, all the instrumentation was installed in the trial embankments and the heating was turned on at trial B. At embankments A and B, the vacuum pumping was turned on 30 and 58 days after beginning of heating, respectively. The fills were raised 60 days after the beginning of vacuum application, so the deposit could achieve the normally consolidated domain.

The experimental site was installed in summer and the vacuum and the heating application have gone through Canadian winter. The heating and vacuum system and the instrumentation were specially protected against the low ambient temperatures of the Canadian winter.

4 INSTRUMENTATION

The instrumentation under the embankments was designed to work under special conditions. When installing instrumentation under vacuum consolidation the main challenge is to maintain the integrity of the PVC membrane against leakage. The instrumentation must also stand negative pore-pressure and at this particular site it should be also able to stand high and low temperatures. For these reasons, vibrating wire piezometers and settlement gauges were used and the calibration was carried out under temperature changes and positive and negative pressures.

All the instrumentation wires were passed through the PVC membrane and were locally sealed. The layout of the instrumentation is shown in Fig. 1. PVC tubes were also installed going through the vacuum membrane and locally sealed, down to the bottom of the crust, allowing *in situ* tests (piezocone and vane tests) to be carried on during vacuum consolidation.

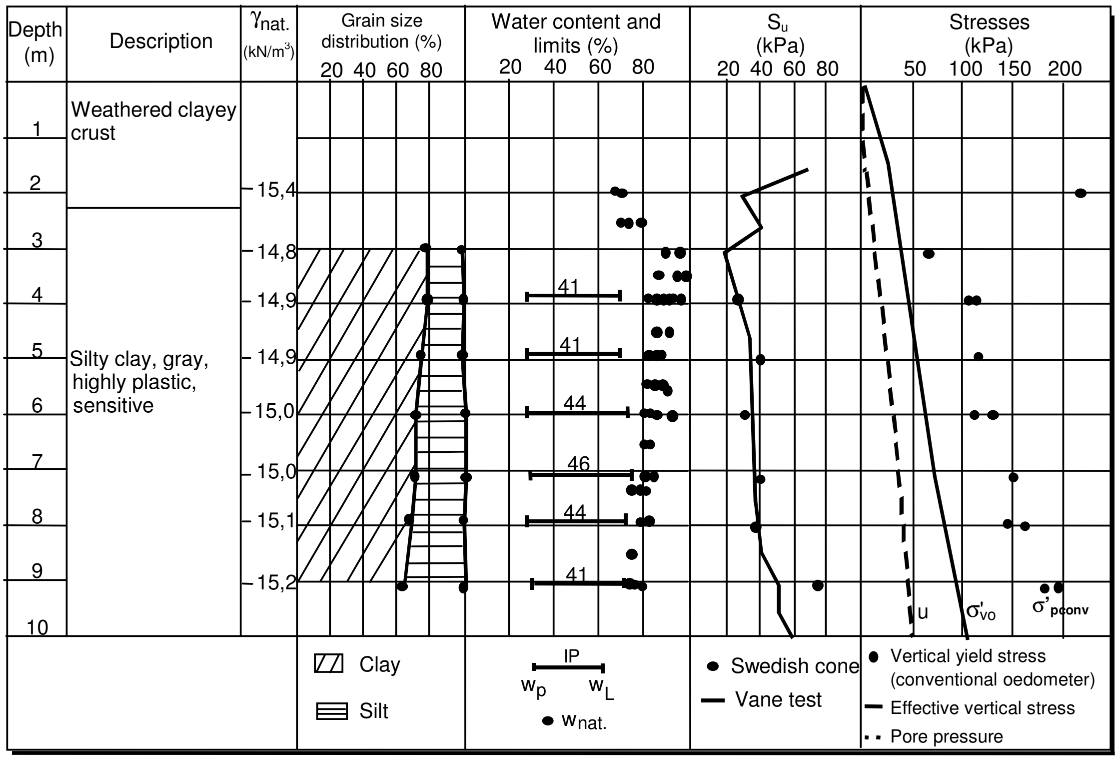

Figure 2. Geotechnical characteristics of Saint-Roch-de-l'Achigan clay deposit (Marques et al. 2000).

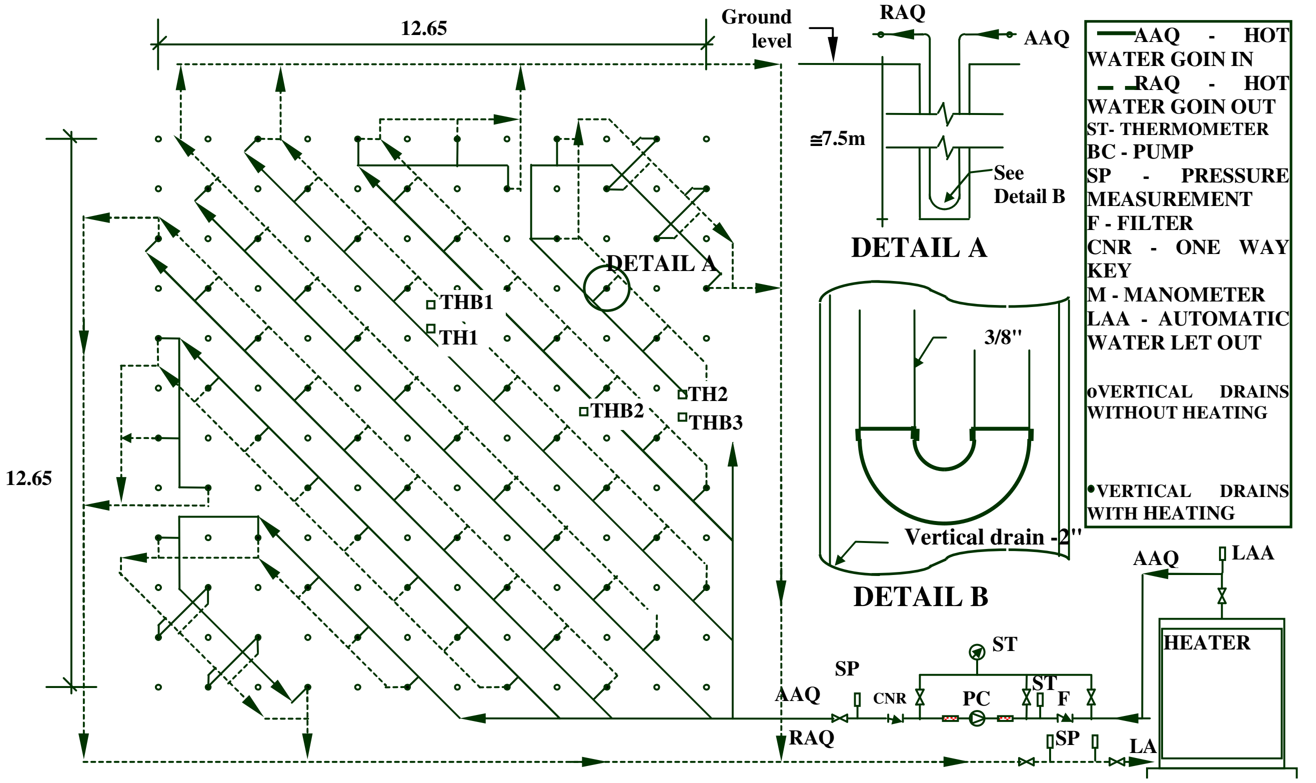

Figure 3. Layout of the heating system.

4.1 Temperatures

Three vertical wood thin piles, with 6 thermistors each (see Fig.4 - detail), at different depths, were installed inside the clay deposit under the embankment B (THB1 to THB3 in Fig.3), and other two under embankment A. Thermistors were also installed inside the sandy fill (TH1 and TH2 in Fig.3).

Seasonal temperature changes were observed inside the crust, but below the crust the initial temperature of the deposit was constant from 6 to 7°C. Figure 4 shows the variation of temperature with time for the thermistors installed in the middle of embankment B (THB1), at 1.2, 2.2, 3.7, .2, 6.7 and 8.2m. The piezometers and settlement gauges also measured temperature, and those measurements were in accordance with those of the thermistors, as shown in Fig. 4.

The initial temperature increase rate was 0.5°C/day. After 58 days of heating, the vacuum pumping was turned on and a drop in the temperature was observed, due to the saturation of the crust and sandy fill with cold water. Since the heating system had to compensate for the influx of cold water, the temperature rate decreased. The heating was carried out for 5 months and the average soil temperature below the crust, from 4 to 7m, increased from 7°C to 39°C.

4.2 Pore pressures

For study purposes the deposit was divided in three sub-layers and the piezometers and the settlement gauges were placed at the middle and bottom of each sub-layer, respectively, as shown in Fig 5, thus allowing calculation of vertical deformations and average pore-pressure of the layers.

Figure 6 shows the pore pressure variation and deformation with time of sub-layer 2. It shows also the suction and embankment heights with time and the initial piezometric profile. The Casagrande piezometers and vibrating wire piezometers installed outside the preloading area indicated that the initial pore pressure profile was not hydrostatic. However due to the small spacing of drains, the eight vibrating wire piezometers installed under the trial embankments after the installation of the vertical drains presented an initial hydrostatic profile. Two vacuum meters were installed at the sand fill of each embankment in order to measure the suction inside the sand fill.

When the trenches were excavated the deposit was unloaded, which was confirmed by the drop in pore-pressure measured by the vibrating wire piezometers.

Due to the small dimensions of this vacuum site the suction was up to 81kPa, while at the majority of sites the vacuum normally achieved is between 70 and 75% of atmospheric pressure.

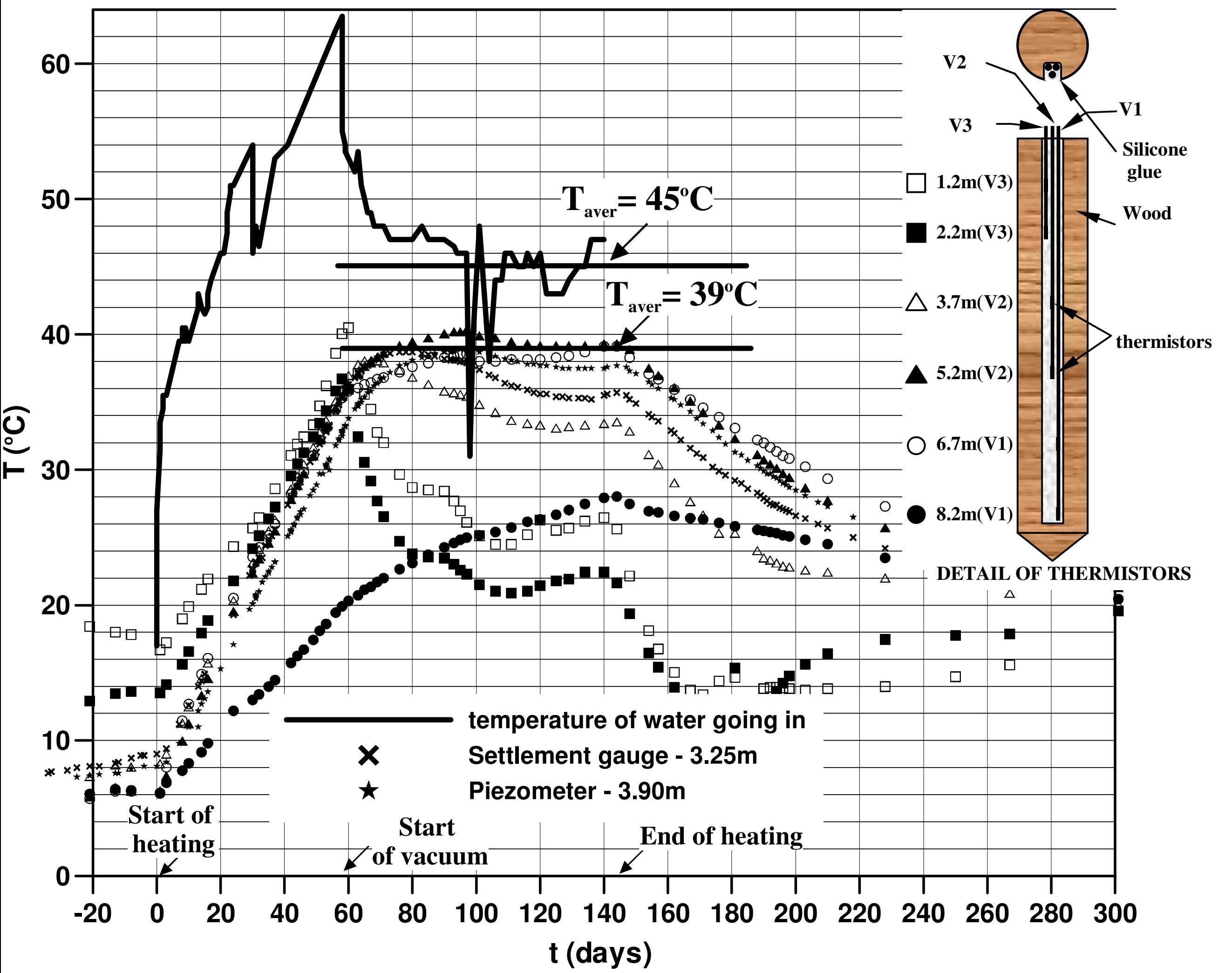

Figure 4. Temperature variation below embankment B.

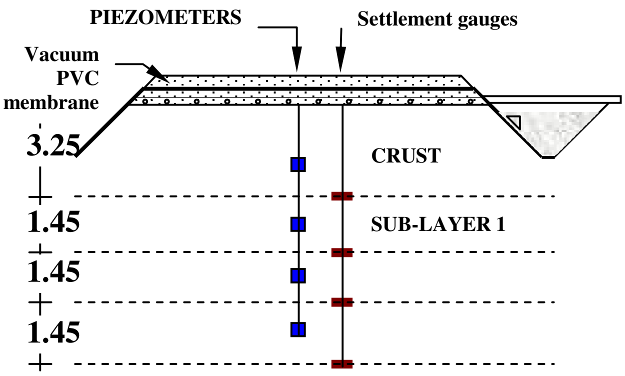

Figure 5. Instrumentation profile.

The pore pressure decreased with time with vacuum application as shown in Fig. 6. When the fill was heightened, it increased accordingly. After that it continually decreased with consolidation and vacuum application. Problems with the vacuum pumping system occurred after 150 days of pumping. The pore pressure profiles increased up to their reference value, thus unloading the deposit. However, after five days of pumping, the piezometers measured negative pressures, a few days before the end of pumping.

The rate of decrease of pore pressures at embankment B was slightly higher, but not proportionally to the increase of permeability with temperature observed in laboratory tests, where an increase of 2.2 times in permeability was observed, when temperature was increased from 10 to 50°C (Marques, 2001).

At the end of pumping the final pore-pressure profile (Δu_f profile) should be parallel to the maximum pore-pressure profile that could be achieved under vacuum. However as shown in Fig. 7, the pore-pressure measured by the wire piezometers were higher than expected at the crust and sub-layer 1, on both fills. Even though from laboratory calibration the piezometers achieved negative pressures of –60kPa, it was observed that the lower *in situ* absolute pressure that could be measured by the piezometers was between –20 and –25 kPa. This could be caused by a dessaturation of the piezometers under long term suction.

4.3 Vertical displacements

Sixteen settlement plates were also installed over the trial embankments, and the total vertical displacements of the eight vibrating wire settlement gauges were also measured. Figure 6 shows the vertical deformation of sub-layer 2.

The heating of embankment B was turned on before the vacuum, when the deposit was overconsolidated and there was expansion, a behavior that was also observed in laboratory. However, after the vacuum consolidation was applied, the settlements of the fills were very similar.

An increase in strain-rate was observed on both embankments when the fill was heightened. The strain rates were about $10^{-9}s^{-1}$, on both embankments when pumping was turned off, which is a very high *in situ* strain rate, when compared to conventional fills.

4.4 Horizontal displacements

Before the excavation of the trench four inclinometers were installed at the embankment toes and one outside the preloading area. In order to measure in wintertime, anti-freeze was mixed with the water inside the inclinometer tubes. However, the acquisition system did not work properly under very low temperatures, below -25°C (-13°F).

Horizontal displacements due only to vacuum consolidation are expected to be very small, since the stress-path due to vacuum preloading is almost parallel to the isotropic axis and the relationship (σ'_v/σ'_h) remains less than K_0. However, when vacuum consolidation is associated with conventional fill, the (σ'_v/σ'_h) could be higher than K_0. Since the fills were not very high at this site, the horizontal displacements were very small even after the end of pumping, when some expansion of the soil mass takes place.

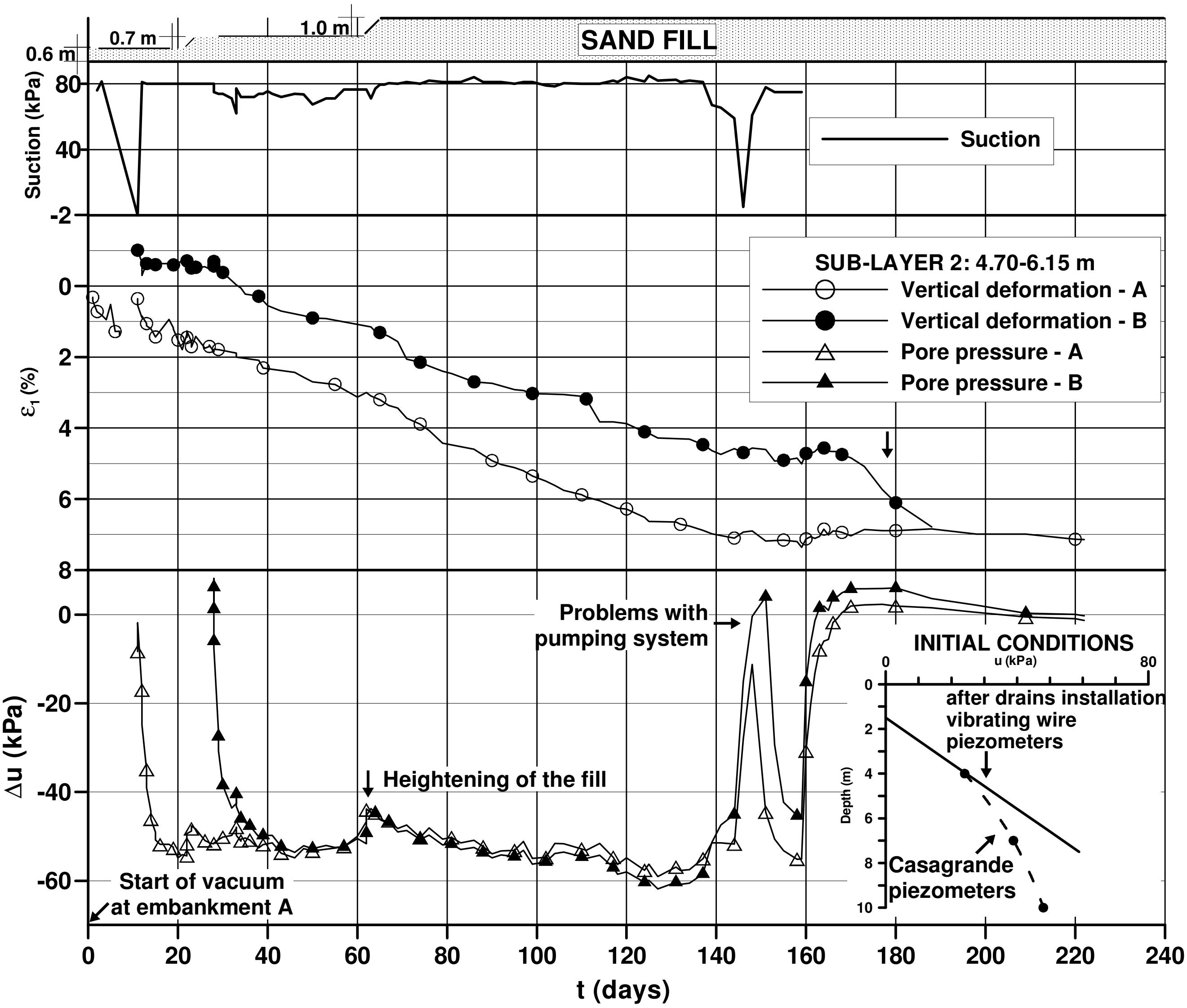

Figure 6. Suction, vertical deformation and pore pressure variation with time at sub-layer 2.

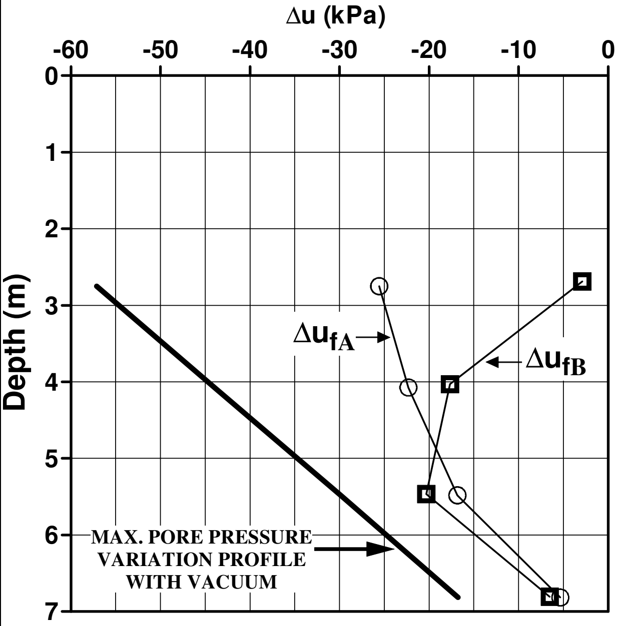

Figure 7. Pore-pressure profiles at the end of pumping.

5 IN SITU COMPRESSION CURVES

The compression curves of the crust and the three sub-layers were obtained after deformation and average pore-pressure calculations. For total stress computation, it was considered stress variation with depth and the unloading due to trenches excavation. The final effective stress (σ'_{vf}) was computed considering maximum pore pressure variation that could be achieved with vacuum. Figure 8 shows the compression curves of sub-layers 2A and 2B. Except for the expansion observed at embankment B, the behavior was similar. The end of pumping on both fills was at the same time, so the strain under fill B was lower than fill A, since vacuum under fill B started 28 days after fill A.

The *in situ* yield stress ($\sigma'_{p\ in\ situ}$) deduced from field compression curves were well defined, and the same under both embankments.

Figure 9 shows the vertical yield stress and *in situ* vertical effective stress profiles. The $\sigma'_{p\ in\ situ}$ were lower than the preconsolidation pressures deduced from piezocone tests (σ'_{pcone}) and those obtained from consolidation tests (σ'_{pconv}). This behavior was expected, since the stress path of vacuum consolidation and field strain rate are quite different of those from laboratory tests.

From laboratory results, $\sigma'_{p\ in\ situ}$ measured at fill B was expected to be 20% lower than fill A, due to heating. This behavior can be explained by the fact that laboratory tests were carried out at a higher range of strain rate, (from $10^{-5}s^{-1}$ to $10^{-7}s^{-1}$) then those observed in the field ($10^{-9}s^{-1}$) and it is possible that at lower strain rates the influence of temperature on preconsolidation pressure is insignificant.

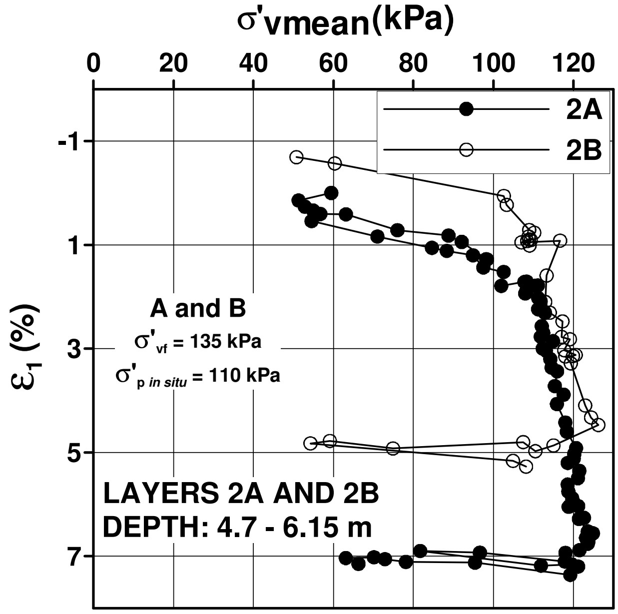

Figure 8. Compression curve of sub-layers 2A (fill A) and 2B (fill B).

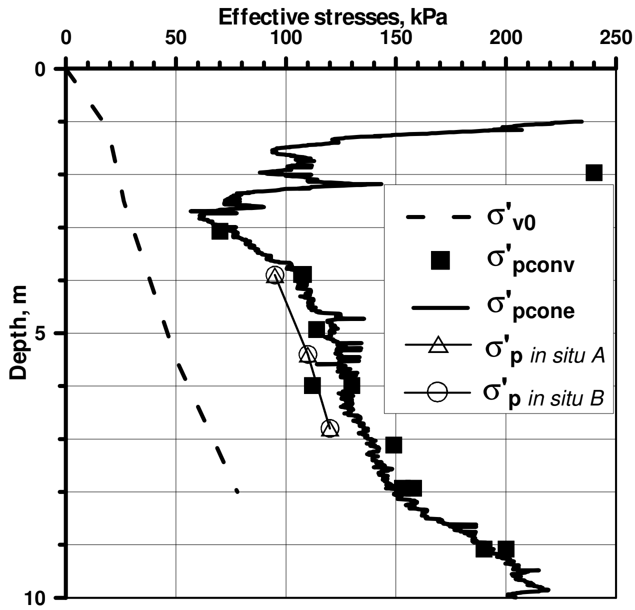

Figure 9. Vertical yield stress and *in situ* vertical effective stress profiles.

6 CONCLUSIONS

The main objectives of the experimental site were to observe the performance of the vacuum system applied on a sensitive Canadian clay deposit, and to study the *in situ* viscous behavior. Better results under vacuum consolidation at this site could not be obtained due to the high depth of the water table and the initial pore-pressure conditions, which decreased the efficiency of the vacuum system. However, the instrumentation used proved to be adequate to the very special conditions on this site.

The heating proved to be a very expensive technique and the *in situ* behavior contradicted the laboratory observations (Marques, 2001; Marques et al. 2003) with respect to temperature variation of embankment B. The stress variation due to vacuum application plus fill was only high enough to surpass the preconsolidation pressure, wich could be the main reason for such behavior. However, it is possible that if the deposit had been well inside the normally consolidated domain, the heating effect on the behavior would be more important, mainly with respect to vertical deformations.

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