Geotechnical Engineering for Transportation Infrastructure, Barends et al. (eds) © 1999 Balkema, Rotterdam, ISBN 90 5809 047 7

Geotechnical characterization of industrial sludges
La caractérisation géotechnique des boues industrielles

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Keywords: sludge, embankment, full-scale test

ABSTRACT: Industrial sludge can be used to construct reservoir dams. The paper deals with the preliminary testing program for the geotechnical characterization of a specific industrial sludge. The sludge material should be used to increase the height of existing reservoir dams. The new dams will be founded on the disposal in the reservoir. A testing embankment with a height of 8 m is being constructed. Pore water pressures and settlements in the supporting disposal as well as in the embankment itself are monitored during and after construction.

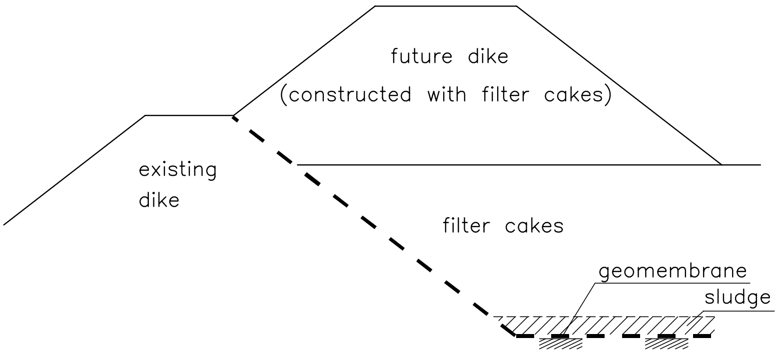
RÉSUMÉ: Il est possible d' utiliser des boues industrielles pour la construction de digues. Cet article traite d'un projet concernant des essais en laboratoire et in situ pour la caractérisation d'une boue industrielle spécifique. Cette matière sera utilisée pour la surélévation des digues existantes autour d'un bassin. Les digues seront construites sur une couche de boue dans le bassin. Une digue expérimentale haute de 8 m sera construite. La hauteur actuelle est de 4 m. La pression de pores et l'enfoncement de la fondation et de la digue sont mesurés.

1 INTRODUCTION

The surface of existing disposals for industrial sludges must allow construction activities. For example the installation of a top liner requires vehicular traffic on the disposal. In other cases the sludge is used for the construction of dikes. Due to the specific behaviour of the sludges their geotechnical characterization is very difficult. The extrapolation of the results of laboratory tests to the real behaviour is not evident. Therefore full scale tests are the most appropriate method for the prediction of bearing capacity, settlements and slope stability. This paper deals with a case study of monitoring of a testing embankment founded on and constructed with filter-pressed sludge. Settlements and changes in pore water pressure are monitored before, during and after the construction of the embankment.

At Tessenderlo Chemie the production of phosphates generates large quantities of sludge. This sludge is pumped into a large bassin. The pumping fluid is recycled. In the bassin the sludge is naturally dewatered. To increase the dry material content and thus the storage capacity of the bassin, the sludge is actually dredged out of the bassin and dewatered by means of a chamber filter press, resulting in a filter cake with a water content of approx. 70 % (dry material content 60 %). The filter cakes are dumped again in the bassin. The dumping of the filter cakes causes the underlying sludge to be squeezed. However it is likely that a small layer of sludge will remain between the bottom liner of the bassin and the layer of dumped filter cakes. Freshly pressed filter cakes have a reasonable indentation resistance against wheel loads, but after compaction and kneeding by vehicular traffic they become very weak and flowable.

A further increase of the capacity of the bassin is planned through increase of the height of the dikes around the bassin, as shown in figure 1. The aim of Tessenderlo Chemie is to construct the new dikes with filtercakes, founded on the layer of dumped filtercakes. The stability of the dikes and of the underlying filtercakes, expected settlements, squeezing of the sludge under the filter cakes are questionable problems.



A preliminary test program has been initiated by the company Tessenderlo Chemie and carried out by the design office Constructor n.v in collaboration with the Reyntjens Labaratory of K.U.Leuven. In a first phase geotechnical characterization of the sludge material was studied in laboratory experiments. The practical implementation of the proposed procedures is now being evaluated in a full scale test that started in October 1997.

2 LABORATORY TESTS

Standard laboratory tests were carried out for soil classification and mechanical properties of the sludge. The results are given in Table 1.

Table 1. Physical and mechanical properties of the filtercakes.

w_l (%)	w_p (%)	I_p (%)	k (m/s)	c' (kPa)	ϕ (deg.)	w_{opt} (%)	$\gamma_{wet,opt}$ (kN/m^3)
85	48	37	$2\ 10^{-9}$ to $5\ 10^{-10}$	3^* 5^{**}	34^* 33^{**}	38	18.8

* CU triaxial test
** CD direct shear test

The determination of the granulometry of the sludge posed several problems. An areometer test carried out with sodiumhexametaphosphate as deflocullation agent was not succesful because the density of the solution did not change in time. Using sodiumpyrophosphate ($Na_4P_2O_7$) gave better results. Figure 2 gives the particle distribution obtained by laser diffraction.

It was observed that the bearing capacity of the compacted filter cakes and the degree of compaction are inversely dependent. This is shown in Table 2: filter cakes were compacted in two different ways and on the samples a CBR test (NF P 94-078) and a vane shear test (ASTM D 4648) were performed. The lowly compacted samples were compacted in a large mold (diameter 152.4 mm) with 3 layers and 33 blows per layer. The rammer (4.536 kg) is dropped from a height of 457 mm (ASTM D 1557). For the highly compacted samples this is 66 blows per layer. The CBR ratio and the undrained shear strength for the low-compacted sample are higher compared with the properties of the high-compacted sample.

A similar behaviour was observed in consolidation tests (ASTM D 2435). A consolidation test carried out on a filter cake after it left the filter press gave C = 40. When the cakes are compacted, C = 21. The higher compressibility of compacted filter cakes is also observed on the site where filter cakes are dumped and spread out by a caterpillar tracked crane. When the crane passes over the dumped filtercakes considerable wave movements are observed and the soil behaves like a water mattress.

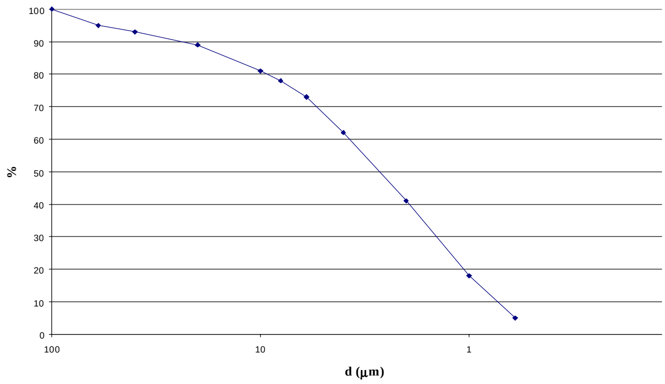


Figure 2. Particle distribution of the sludge

Table 2. Properties of samples with different compaction

degree of compaction	γ_{wet} (kN/m^3)	γ_d (kN/m^3)	w (%)	CBR ratio	c_u (kPa)
low	15.1	8.2	83	0.35*	19
high	15.2	8.5	78	0.25**	16

* penetration of 5.0 mm at 0.037 Mpa
** penetration of 5.0 mm at 0.026 Mpa

Since the exact degree of compaction on the site is unknown and the presence of a layer of unpressed sludge under the filter cakes is expected, it was decided to construct a test embankment to observe the real behaviour during and after construction.

3 TEST EMBANKMENT

3.1 *Location of the testing areas*

A test embankment was constructed to monitor the consolidation of the foundation of the dike and to check its stability.

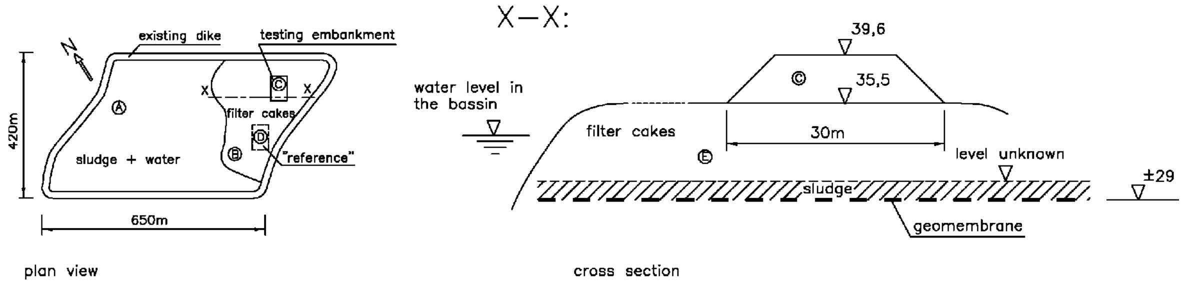


Figure 3. Situation of the site

Figure 3 represents the situation of the embankment in the bassin and its cross-section. The major part of the bassin is not filled with filter cakes: it contains unfiltered sludge, covered by water (zone A in figure 3). Up to now only a small part of the entire bassin is filled with filter cakes (zone B and E in figure 3). The testing embankment (zone C in figure 3) is constructed on this layer of filter cakes. The embankment is realised in two main stages: in the first stage the height is 4 m; the second stage (another 4 m) wil be executed when the underlying layer of filter cakes is sufficiently consolidated. The dimensions of the embankment at its base are 30 ×60 m. The slope angle is about 45°. The exact thickness of the underlying layer of filter cakes ('E') is variable. The thickness of layer E is about 5 m. Area D in figure 3 is a testing area on which no embankment will be put. These reference measurements will be used to monitor the consolidation of filtercakes without topload and to evaluate the influence of external factors as there are: the water level in the bassin, climatic influences,...

3.2 *Measuring equipment*

To monitor the settlements of the layer of filter cakes, 11 settlement plates are placed before the construction of the embankment. For the measurements of the pore water pressures, piezometric tubes (6) and pressure cells (6) are provided. Additional settlement plates and water pressure cells

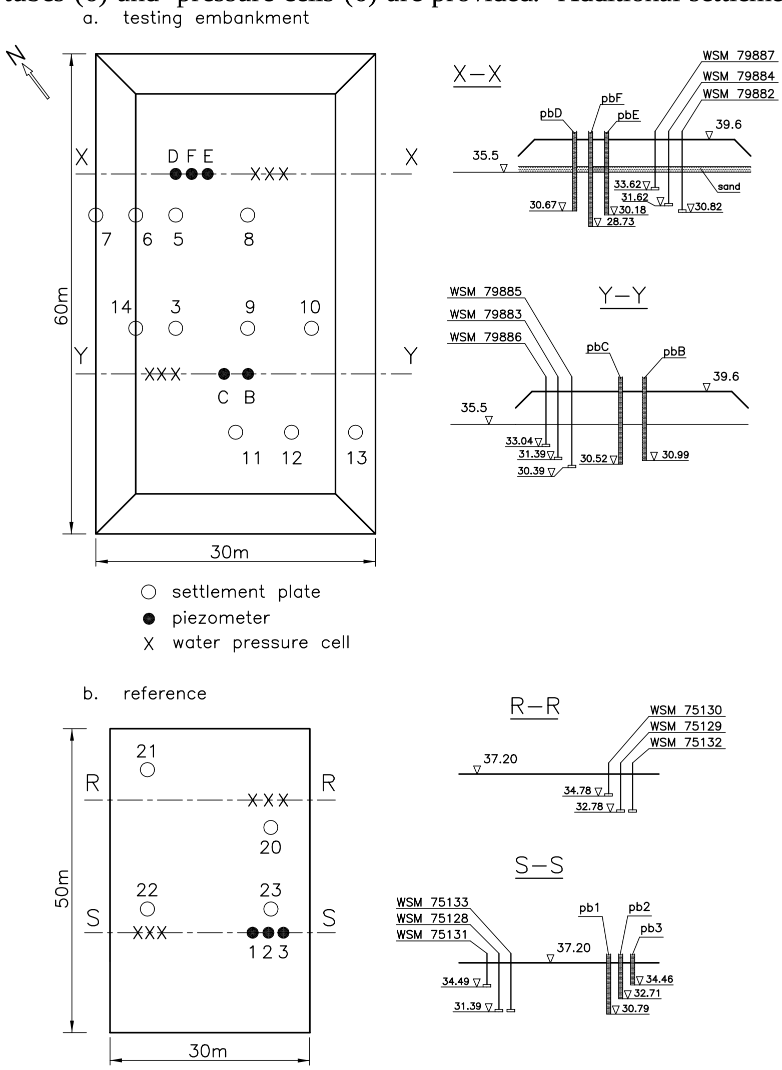


Figure 4. Measuring equipment in the testing embankment

are placed in the embankment itself, to monitor the influence of the additional 4 m of filter cakes that will be put on the embankment in the future. The locations of the settlement plates, the piezometric tubes and the water pressure cells are shown in figure 4. The settlement plates are indicated with the code 'ZB', the piezometric tubes with 'PB' and the water pressure cells with 'WSM'.

The reference measurements are done by 4 settlement plates, 6 water pressure cells and 3 piezometric tubes (see figure 4). More sophisticated equipment is not installed in this phase of the project.

3.3 *Results*

The installation of the piezometric tubes and the water pressure cells took place in October - November 1997. The installation of the measuring equipment posed some practical problems. It was impossible to make the bore holes sufficiently deep starting from the ground level of the layer of dumped filter cakes. Bore holes of more than 2.5 m deep collapsed. Therefore a pit was dug by a crane. The bore holes were made starting from the bottom level of the pit. The filling of the pit had to be done with extremely care to avoid damage to the piezometric tubes. During the construction the piezometric tubes had to be protected by putting large steel tubes around them to avoid damage by the large lumps of filter cakes.

The construction of the embankment began in April 1998. It was decided to divide the testing embankment into 2 parts. The first half (in which section Y-Y of figure 4 is situated) is constructed directly on the underlying layer of filter cakes. Under the second half (section X-X) a drainage layer is provided consisting of 30 cm of sand and drainage pipes (see figure 5).

The construction took place in several phases, depicted in figure 5 and briefly described hereafter:

I: filter cakes are put around the perimeter of the future embankment (measurement: 7 April 98)

II: the first half of the testing area is raised until 2 m (measurement: 16 April 98)

III: the first half of the embankment is realised: height about 4 m (measurements: 29 April 98, 8 and 15 May 98)

IV: the drainage sand is put on the second half of the testing area(measurement: 25 May 98)

V: the second half is raised until 2 m (measurements: 5 and 15 June 98)

VI: the second half is raised until 4 m (measurement: 30 June 98)

VII: egalisation of the crown and the slopes of the embankment (measurements since 9 July 98).

Before, during and after these works measurements are made. The variations of the water pressures for the testing embankment are represented in figure 7. Figure 6 gives the results for the reference area. The settlements are represented in figure 8.

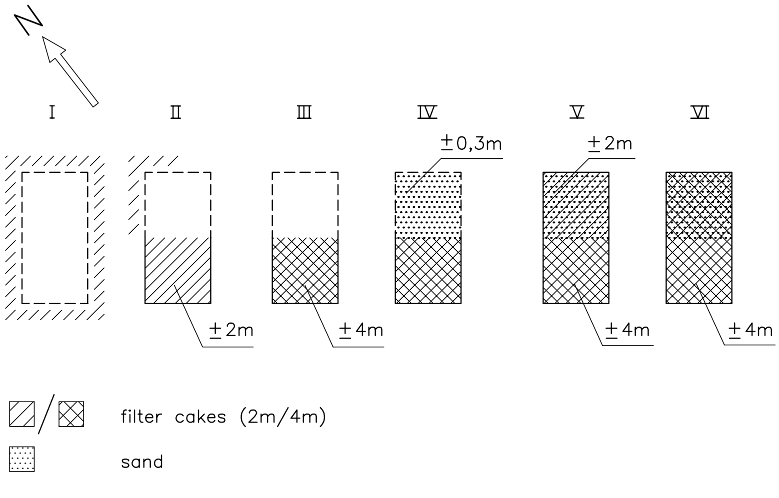


Figure 5. Construction phases of the embankment

The results of the settlement plates on top of the embankment and of the water pressure cells in the embankment are not given. After 30 June 98 piezometric tube PB A is not used anymore: it was damaged during the activities of phase VII.

By measuring the levels of the tops of the piezometric tubes it is observed that they sink into the layer of filter cakes. Since their placement PB B and PB C sank 230 mm, resp. 380 mm downwards. For the other piezometric tubes the situation was worse: PB D: 1590 mm, PB E: 720 mm and PB F: 1100 mm. These changes were taken into account when handling the measured levels. For the water pressure cells this is more difficult: it is impossible to say how much they have sunk, so correction is not obvious. It is likely that one or more cells have sunk for more than one meter, which means that the calculated piezometric height is one meter lower. However, this possibility should be taken into account when interpreting the results rather than when calculating the piezometric heights.

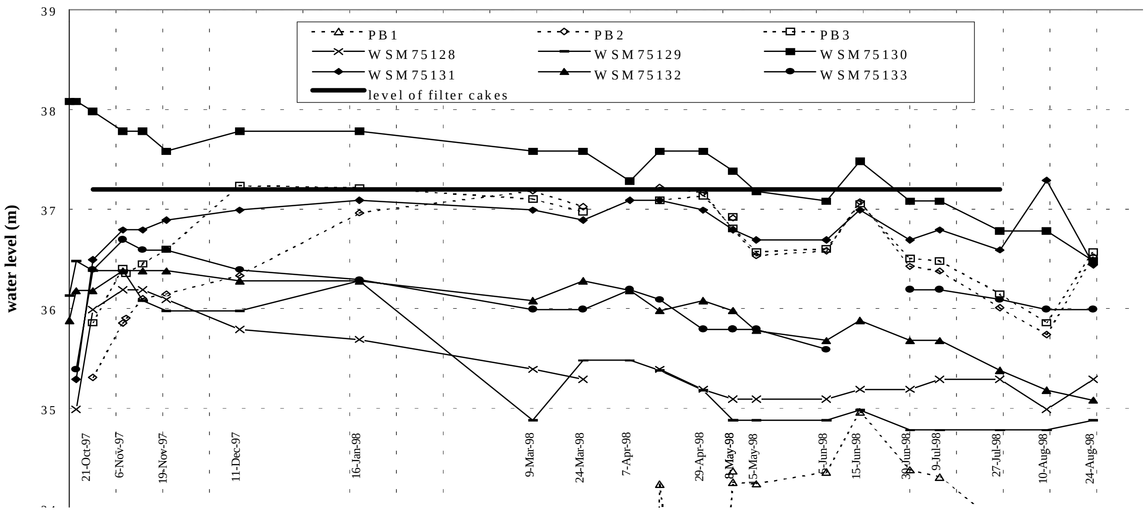


Figure 6. Piezometric heights for the reference area

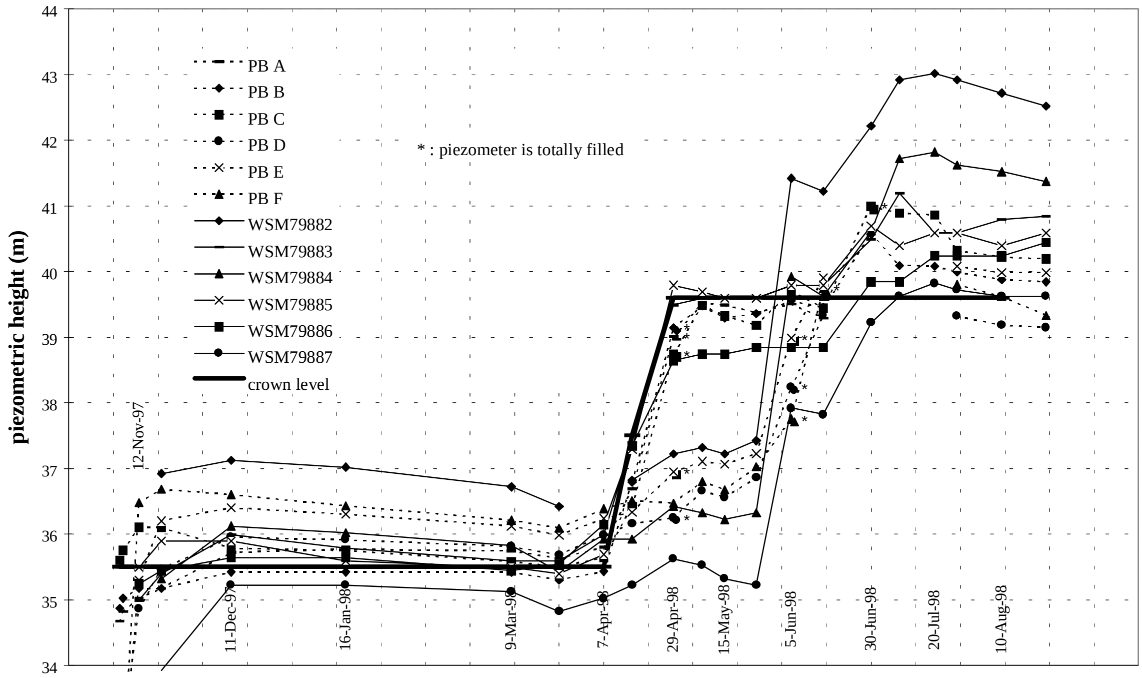


Figure 7. Piezometric heights for the testing embankment

In figure 7 the points marked with a '*' indicate that the piezometric tubes were totally filled with water. The calculated piezometric height is an underestimation of the real pressure in the piezometric tube.

3.4 *Discussion*

At the beginning of the measurements the piezometric heights were increasing, since the piezometric tubes and the waterpressure cells had to be filled with pore water. After that period piezometric heights did change slowly and were slightly decreasing, due to the consolidation process of the layer of filter cakes. The measurements for section X-X (figure 4) give generally higher piezometric heights than section Y-Y. It was observed, during installation of the pressure cells that the filter cakes at the bottom of the bore hole were very soft and very wet. This could explain the higher water pressure for this section.

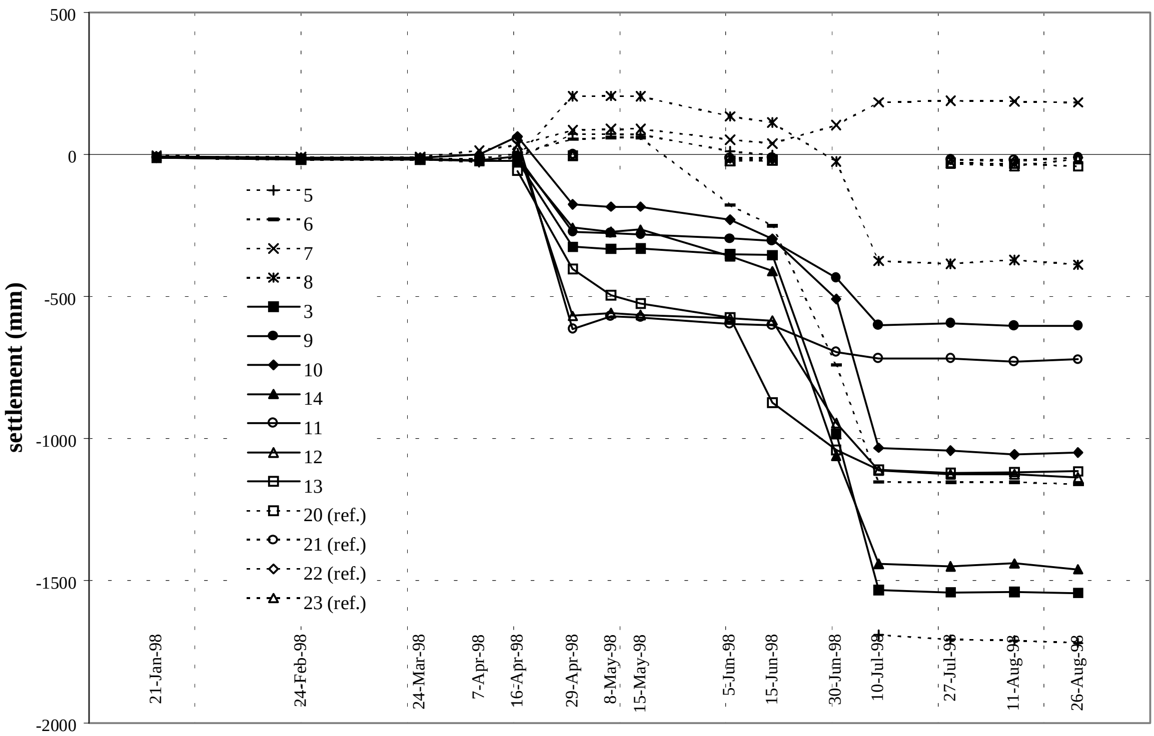


Figure 8. Settlements: testing embankment and reference area

The measurement of 7 April 98 gives higher piezometric heights than the previous measurement, due to the increased load of the filter cakes on top of the testing area (phase I). Settlements were increasing, but not very firmly.

During phases II and III the piezometric heights indicated by the equipment under the first half (PB A, B,C and WSM 79883, 79885 and 79886) increased. Comparing the levels measured at 29 April 98 and at 7 April 98, the increase ranges between 3.5 m and 4.5 m. The settlements measured with ZB 11, 12 and 13 are about 600 mm. ZB 3, 9, 10 and 14 give settlements of about 300 mm. These plates are situated at the transition of the raised and the non-raised area. The effect of phases II and III on the results of section X-X is smaller: the average piezometric height rise is about 1.5 m. ZB 5, 6, 7 and 8 give a rise of the soil, due to volumetric compensation of the settlements of the first part.

A similar fenomenon was observed during phases V and VI: the effect on section X-X was considerable, while it was rather small on section Y-Y. Piezometric heights in section X-X did firmly rise (4 m). ZB 5, 6 and 8 indicated large settlements (during phases II and III they were lifted up), while ZB 11, 12 and 13 continued setting. The settlements indicated by ZB 5 must be interpreted with caution: at 30 June 98 measurement of ZB 5 was impossible because it was buried under filter cakes. At 9 July it was repaired, but a considerable crookedness was observed. This might affect the future measurements of ZB 5.

The activities during phase VII caused miror variations in the piezometric heights. Compared with the initial situation (24 March 98), a rise of the piezometric height with 4 to 5 meters took place. The total settlements vary with the location of the plates. Leaving ZB 5 aside, the largest settlements are for ZB 3 and 14 (1500 mm), situated between sections X-X and Y-Y. All the other points indicate settlements larger than 500 mm, except ZB 7. ZB 7, placed outside the embankment, indicates positive settlements: it is lifted up as a result of the volumetric compensation. This uplifting behaviour was also observed for a conveyer located 20 to 25 m from the testing embankment. Due to differential uplifting displacements, action had to be taken to guarantee the good functioning of the conveyer. 12 additional settlement plates are placed to quantify the uplifting behaviour of the area around the embankment as a result of raising the embankment. During the construction of the embankment the piezometric heights measured at the reference area kept decreasing, due to the consolidation process of the filter cakes.

4 CONCLUSION

The uncertainty about the interpretation of the results of laboratory tests made it necessary to observe the behaviour of the sludge/filter cakes by monitoring a testing embankment. The monitoring consists of measuring settlements and pore water pressures before, during and after construction. Large displacements are observed, with consequential raising of pore water pressures. The large settlements take place during and immediately after loading the filter cakes. They are the result of both vehicular traffic and static load due to the weight of the filter cakes.The last measurements indicate that the settlements hardly change, while pore water pressures are slowly decreasing. A non-negligible uplifting behaviour of the surrounding soil is observed and can cause difficulties for the equipment. When sufficient consolidation is reached the embankment will be raised with another 4 m of filter cakes. Settlement plates are installed to measure the effect of this on the uplifting behaviour of the filter cakes next to the embankment. These experimental data will guide the design and planning of the future dike construction.