Geotechnical behaviour of an industrial sludge

Compartément géotechnique d'une boue industrielle

J. Tennekoon, D. Van Gemert & J. Maertens
Department of Civil Eng., Katholieke Universiteit Leuven, Belgium; janaka.tennekoon@bwk.kuleuven.ac.be

J. Houtmeyers
Tessenderlo Chemie, Ham, Belgium

J. D'haeyer
Constructor n.v., Antwerpen, Belgium

KEYWORDS: Sludge, geotechnical characterisation, test embankment, PLAXIS

ABSTRACT: A fine-grained industrial sludge is to be used to construct an embankment founded on previously disposed and comparatively consolidated sludge. Various laboratory and in situ tests have been carried out to ascertain the engineering properties of the sludge and to investigate the stability of the dam. The general properties and behaviour of the sludge have been found to correspond closely to that of clay and it is suitable for the construction of the dam.

RÉSUMÉ: Une fine boue industrielle sera utilisée pour l'utilisation dans la construction d'une digue, au dessus d'une boue similaire, dragée, filtre-pressée et déposée auparavant dans le bassin. Des essais en laboratoire et in situ ont été examinés pour la détermination des caractéristiques mécaniques de la boue, et pour l'étude de la stabilité de la digue sur sa fondation de boue traitée. Les propriétés de la boue ressemblent assez bien à celles d'une argile, et ils sont appropriées à la construction de la digue.

1 INTRODUCTION

Land disposal of sludges requires the adequate investigation of their engineering properties. Several studies have been conducted in the past to investigate sludges of different origins such as FGD (Hagerty, Ullrich and Thacker, 1987), paper mill (Moo-Young and Zimmie, 1996), municipal sewage and manufacture of steel (Alvi and Lewis, 1987) sludges. These sludges have been found to have somewhat similar geotechnical properties such as high moisture contents, high compressibility and low resistance to shearing. However, their individual behaviours can differ significantly and they may have poor structural characteristics thus necessitating comprehensive and individual analysis.

This paper deals with the study of a sludge in order to use it for the construction of an embankment with a view of increasing the storage capacity of an existing disposal site. The dike will not only be constructed with the sludge but will also be founded on previously disposed sludge. At Tessenderlo Chemie in Ham, Belgium, the production of phosphates and other products results in the generation of large quantities of a fine-grained sludge whose main constituent is SiO_2-bonded calcium fluoride (CaF_2) (Delveaux and De Broe, 1993). This sludge is pumped, along with water, into a large basin and allowed to de-water naturally. The dry material content of the sludge is enhanced mechanically by means of a chamber filter press and the resulting filter cakes are disposed in the basin.

Laboratory and in situ tests have been carried out to accurately ascertain the engineering properties of the sludge material. In order to overcome uncertainties and identify macro effects, an instrumented full scale test embankment has been constructed with regular measurements of settlements and pore water pressures in both the embankment and the underlying sludge. A numerical model of the trial embankment and the underlying sludge has also been analysed to identify their most likely behaviour over time. The numerical model is made with the help of the PLAXIS software package. Some of the main results from the geotechnical investigation, measurements from the trial embankment and the numerical simulation are summarised in this paper.

2 SITUATION

The sludge disposal basin is located at Ham, Belgium encompassing a total area of about 273,000 m^2. An outline of the basin is shown in figure 1 and the cross-sections of the existing dam and the proposed 8 m high embankment founded on a 7m thick sludge layer, are shown in figure 2.

An impermeable geomembrane has been provided at the bottom of the basin to prevent the contamination of groundwater by the leachate from the sludge basin. The dike is to be constructed on a layer of relatively compact and drained sludge whose exact degree of compaction is unknown. There is a possibility that the sludge just above the geomembrane is wetter and less compact than the overlying sludge because from here the sludge is not dredged and mechanically de-watered in order to avoid damaging the geomembrane. Hence, the behaviour of the sludge under loading is uncertain.

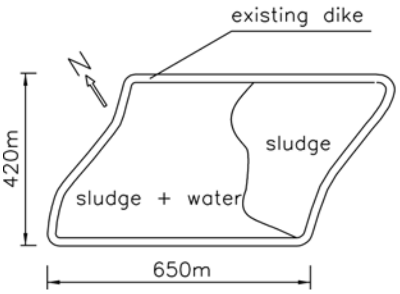

Figure 1. Disposal basin

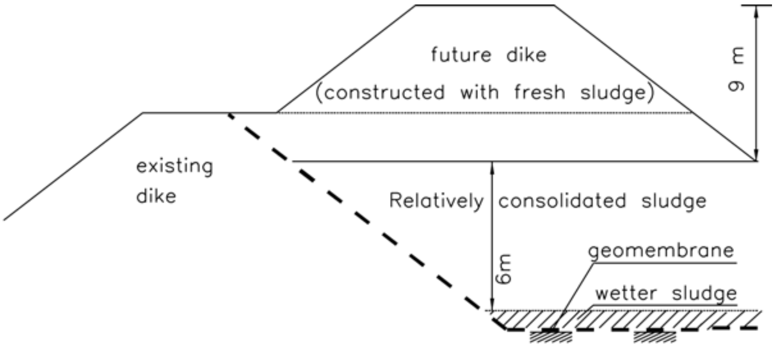

Figure 2. Cross-section through the existing and proposed dikes

3 GEOTECHNICAL CHARACTERISATION

3.1 Laboratory tests

Various standard laboratory tests have being carried out on both disturbed and undisturbed samples to ascertain some of the important mechanical properties of the sludge. The tests executed include moisture content determination, areometer, x-ray diffraction, liquid and plasticity limits, permeability, consolidation, optimum water content and density, vane shear and direct shear. The mechanical properties of the sludge determined from some of the above tests are given in table 1.

A general conclusion that can be made from the results of table 1 and the granulometric analysis is that the basic physical and mechanical characteristics of the sludge is typical of fine grained soils. However, the optimum water content at 38% is high even for clayey soils. A reason for this is that the sludge particles have a high affinity to water molecules.

Table 1. Basic geotechnical properties (Delveaux and De Broe, 1993)

W_L	W_P	Ip	c_u	ϕ_u	k (m/s)	w_{opt}	$\gamma_{wet,opt}$	$\gamma_{dry,opt}$
85%	48%	37	3-5 kPa	33^O	1-5 x 10^{-9}	38%	18,8 kN/m^3	13.6 kN/m^3

In addition to the above, permeability and consolidation characteristics under different vertical stresses were also investigated. These results are summarised in table 2.

Table 2. Permeability and consolidation characteristics

Stress (kPa)	Permeability, k (m/s)	Consolidation coefficient (m^2/year)	Coefficient of volume compressibility (m^2/MN)
12.75	5.10E-10	2.02	2.83
25.5	5.06E-10	0.02	2.05
51	4.76E-10	0.06	1.67
102	3.34E-10	0.61	1.12
204	2.63E-10	1.43	0.82
408	2.39E-10	1.67	0.62

As expected there is a general decrease in permeability with increasing stress. The consolidation and volume compressibility coefficients are typical of clay soils indicating high compressibility but very low rates of primary consolidation (Head, 1982). The relatively high value at low stresses is possibly due to the sludge being normally consolidated at this load.

An analysis of the sludge under the electron microscope clearly showed the sludge particles having a strong tendency to flocculate (Delveaux and De Broe, 1993). The reason for this is the presence of salts and chloride ions which enhances the interaction between the clay particles.

3.2 Field tests

The in-situ tests carried out on the sludge are density measurement, permeability measurement, vane shear tests and cone penetration tests. The results of he first two are shown in table 3.

Table 3. Results of in-situ density and permeability measurements

Permeability, k (m/s)	Density, γ (kN/m^3)	Moisture content, w (%)
2 to 3 E-09	12 to 15	80 to 95

The in-situ permeability measurement leads to a somewhat higher value than in the laboratory analysis. This can be attributed to the presence of laminations and vertical fissures in the sludge which enhance the flow of water.

The vane shear tests and cone penetration tests have indicated that the shear strength of the sludge increases from 20 to 30kPa with depth. However, the rate of increase of shear strength with depth and the actual values show marked variations from place to place. This is certainly due to the non-uniformity in the degree of compaction of the sludge at the locations tested.

3.3 Remarks

It can be concluded that the behaviour of the sludge is similar to that of clay (Head, 1982). However, the high water content, due to adhesion of water molecules to the sludge particles, and the presence of various ions cause a degree of uncertainty in the behaviour of the material especially in the long term. For this reason, it is not pragmatic to apply all theories that are valid for clays to the sludge. Furthermore, the general macro-fabric of the sludge is not represented accurately in specimens that are used for the laboratory tests. With the above remarks in mind it was decided to construct a full-scale test embankment to observe the real behaviour of the sludge during and after construction.

4. TESTS ON FILTER CAKES

4.1 Tests on individual filter cakes

The filter cakes arising from the mechanical de-watering process consist of 3cm thick rectangular blocks, which have been subjected to a compressive force of about 1400kPa. In order to identify any variations in their engineering properties some of these filter cakes were individually analysed for water content, porosity and shear strength. The results confirm the heterogeneity of the filter cakes.

4.2 Tests on filter cake mixes

Consolidation and shear tests (direct shear and vane) were carried out on filter cakes that had been stacked horizontally and in a mixed manner. Fresh filter cakes and filter cakes that had been dried at room temperature for 1 and 7 days were used. These samples were first subjected to a cyclic load prior to vane testing. The effect of re-wetting samples that had been dried and loaded was also studied. The results are given in figure 3. Results of consolidation tests carried out on horizontally and in a mixed manner stacked filter cakes are shown in figure 4.

It is apparent that the drying of filter cakes result in their strengthening. However, on re-wetting the strength decreases considerably. This is due to drying followed by loading and re-wetting causes a breakdown of their structure with strong inter-particle bonds resulting in a powdery material that is unable to regain all of its strength even after re-wetting. The settlement of the two differently stacked samples differs clearly with a relatively large degree of immediate settlement especially for the mixed filter cakes. Furthermore, the immediate settlements constitute a greater potion of the total settlement for both the horizontal and mixed stacked filter cakes and for all loading steps. These are a further indication of the heterogeneity of the filter cakes. The expected settlement on site will also show such large immediate settlements as well as marked variations due to the heterogeneity of the filter cakes.

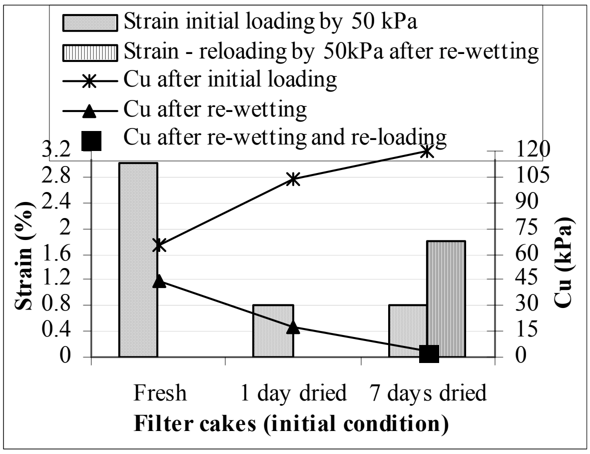

Figure 3. Results of compression and vane tests (Van Der Veken, 2002)

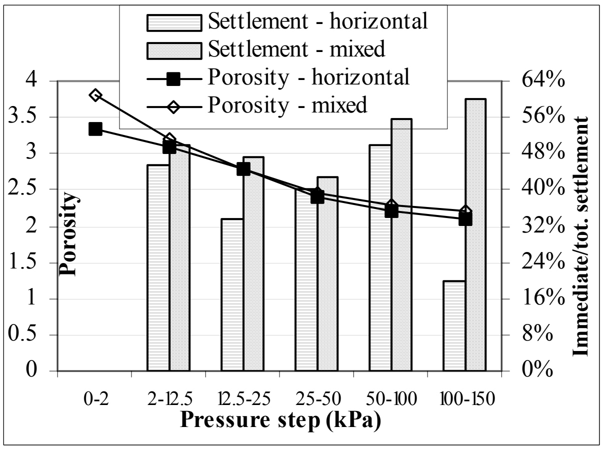

Figure 4. Results of consolidation tests (Van Der Veken, 2002)

5. TEST EMBANKMENT

5.1 Location & measuring instruments

The 30x60m embankment of height 6m is constructed on a layer of sludge of about 7m thickness and in two stages of 4m and 2m with a period of about 10 months allowed for consolidation. Instruments were installed in the dike and the underlying sludge to monitor settlements (ZB) and pore water pressures (WSM & PB). On one half of the embankment two sand layers of 30 cm thickness were provided at the base of the dike and at the top of the first raise, to enhance drainage. Settlement plates were installed adjacent to the dike before the second phase to measure the degree of bulging of the sludge around the embankment, which were visible after the first raise.

5.2 Results

Measurements have been made at regular intervals during and after the construction period. Figure 5 shows the water pressures in the embankment for the sections with and without drainage sand, X-X and Y-Y respectively. The water pressure meters, WSM 80813-4, were installed in the embankment after the first phase. The settlement monitors placed adjacent to the dike showed significant rising of the ground during the construction of the dike. This bulging was in excess of 1 m in places.

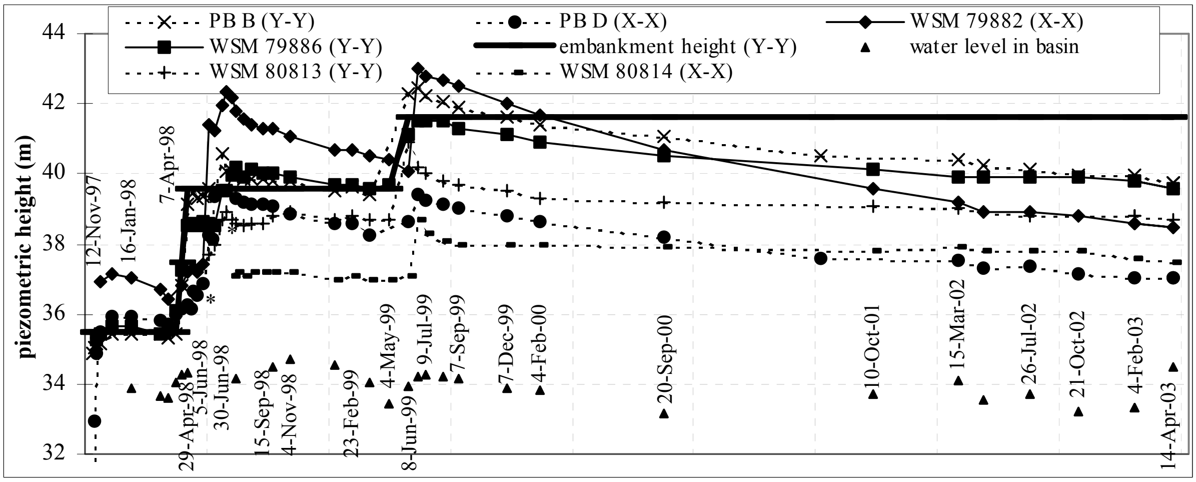

Figure 5. Results of water pressure measurements

In general the piezometric levels closely follow the construction of the dike. During construction, the pore pressures increases followed by slow dissipation. The rate of dissipation is visibly faster in the section of the dike with drainage sand.

The settlements below the dike vary between 0.4 to 1.6m during the first raise and between 0.1 to 0.5m during the second raise. The settlements during the two consolidation periods are about 0.3m at the most. Hence, of the total settlement, over 90% occur as immediate settlement during the raising of the embankment. This is most certainly due to the squeezing of the sludge under the embankment. The settlement plates next to the test embankments showed lifting by up to 1 m in this region. This also occurred immediately after the raising of the embankment and thereafter the bulge decreased gradually. It can be concluded that the settlement under the dike is mostly plastic (squeezing of the sludge) and to a lesser extent elastic (causing bulging of the sludge around the embankment).

6 NUMERICAL MODELLING

6.1 Introduction

For the numerical analysis, the PLAXIS finite element code for geotechnical analysis has been used. The analysis was carried out in the undrained state using the parameters determined from the various tests as the initial input while the measurement data have been used to calibrate the model and obtain more accurate values for the parameters. Two material models were assessed; an elasto-plastic Mohr-Coulomb (MC) and a hardening-soil (HS) model where soil stiffness is described more accurately and the stress dependency of stiffness moduli are accounted for (Brinkgreve and Vermeer, 1998).

6.2 Results

The best results (closest fit between measured and model values) were given by the HS model. The excess water pressures are close to the measured values but the same is not true of the settlements. The main problem with the model is that it is unable to simulate the very large instantaneous settlement that the sludge undergoes during loading. Some of the results are shown in figure 6.

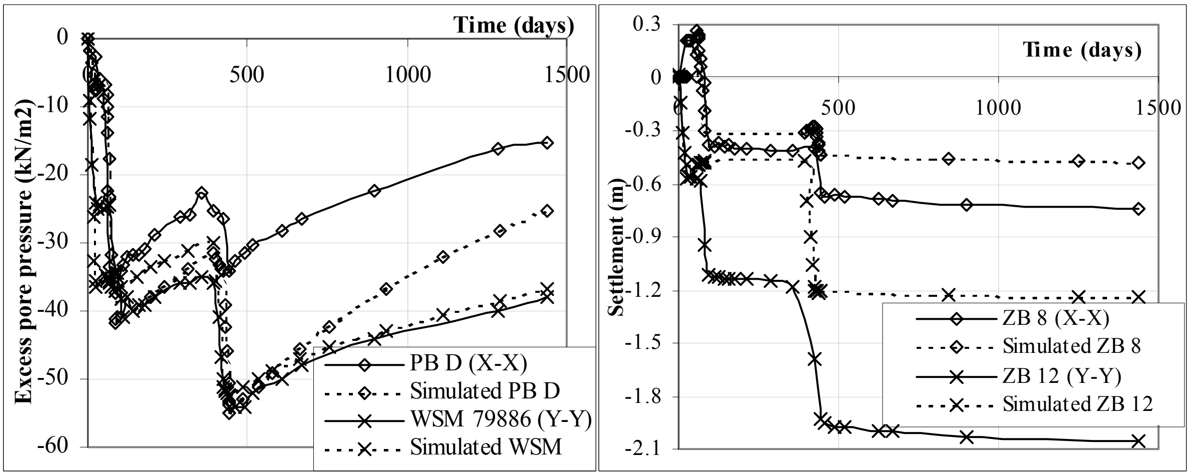

Figure 6. Comparison of some measured and simulated (HS model) values (Tennekoon, et al 2002)

7 CONCL USIONS

The main geotechnical features of the sludge can be characterised as follows:

- relatively high porosity and water content with strong affinity to water molecules;
- high compressibility (mainly primary but also some secondary) and low bearing capacity;
- high degree of heterogeneity of the filter cakes;
- loss of strength after drying loading and re-wetting.

The construction, monitoring and assessment of the test embankment provided an insight into the actual behaviour of the sludge, which was hitherto uncertain. The provision of drainage layers does lead to faster consolidation.

The simulation model and its calibration did show some shortcomings, with regards to the immediate settlement. However, considering the simplicity of the model compared to the sludge heterogeneity and the accuracy of some of the measuring instruments these shortcomings may be acceptable. These are nevertheless important factors that must be overcome or minimised during further testing and analysis.

7 REFERENCES

Alvi, P.M. and Lewis, K.H. (1987). Geotechnical Properties of Industrial Sludge. Proc. of International Symposium on Environmental Geotechnology, Philadelphia, Vol. 2, 57-76.

Brinkgreve, R.B.J. and Vermeer, P.A. (1998). Plaxis – Version 7. A. A. Balkema, Rotterdam, 400 pp.

Civieltechnisch Centrum Uitvoering Research en Regelgeving, (1993). 162 Construeren met grond. CUR, Gouda, 564 pp.

Delveaux, T. and De Broe, E. (1993). Recyclage van Afvalslib voor Dijkbouw. Thesis, Department of civil Engineering, K. U. Leuven, 133 pp.

Hagerty, D.J., Ullrich,C.R. and Thacker, B.K. (1977). Engineering properties of FGD sludges. Proc. Of the conference on geotechnical practice for disposal of solid waste materials, ASCE, 23-40.

Head, K. H. (1982). Manual of Soil Laboratory Testing – Vol. 2: Permeability, Shear Strength and Compressibility Tests. Pentech Press, Great Britain, 747 pp.

Moo-Young, H.K. and Zimmie, T.F. (1996). Geotechnical Properties of Paper Mill Sludges For Use in Landfill Covers. Journal of Geotechnical Eng., ASCE, 768-775.

Tennekoon, J., Van Gemert, D., Maertens, J., Houtmeyers, J. and D’haeyer, J. (2002). NUMGE 2002. Proc. 5th European Conf. Numerical Methods in Geotechnical Engineering, Paris, LCPC, 421-428.

Van Der Veken, J. (2002). Bouw van dijken met en op industrieel slib. Thesis, Department of Civil Engineering, K. U. Leuven, 100 pp.