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Geotechnical properties of sewage sludge

Les caractéristiques d'une boue originée des déchets

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ABSTRACT
In the UK ever-increasing volumes of sewage sludge are being deposited in engineered landfills. To design these facilities properly it is necessary to quantify the engineering behaviour and properties of this sludge, which is not a true geotechnical material. Although sewage sludge has a very open structure it exhibits very low permeability and attempts have been made to use additives to improve is drainage characteristics.

RÉSUMÉ
Dans le Royaume-Uni il faut se débarrasser des quantités immenses de la boue qui reste après le tratement des vidages dans les centres d'enfouissement des déchets. Afin de dessigner le tas des déchets il faut définer le comportement et les propriétés mecaniques de cette boue, même qu'elle ne soit pas vraiment un matériau géotechnique. Cette boue possède une structure très ouverte mais elle a la perméabilité tres très petite et l'Auteur a fait quelques essais pour ameliorer les caractéristiques d'une boue typique.

1. INTRODUCTION

In the UK many sewage works have old sludge-retention lagoons which were constructed by excavating a suitable void space and using the excavated material to build up banks surrounding the lagoon to increase its volume - these lagoons were not engineered for stability or containment. With time evaporation, settlement of solids and decanting surface water can lead to substantial thickening of the stored material. However there is a limit to the thickening achieved by this 'natural' process and sludge may retain a thixotropic nature indefinitely, especially if the deposit is several metres deep. In 1992 a rotational shear failure of lagooned sewage sludge prompted a major sludge flow (200,000m^3) that blocked a 30m-wide river (Claydon et al, 1997). Sludge had been stockpiled at the site since 1906 and in places it had attained a depth of 25m.

Today the most common final repository for sewage sludge is an engineered landfill. Unfortunately, the fine semi-liquid waste can infill the voids within refuse so that the overall shear strength of the waste mass is reduced. In Germany, landfills filled almost entirely with sewage sludge have been created, with minimum requirements for shear strength and solids content being specified for the incoming sludge.

Despite the origins and nature of sewage sludge, currently the only logical way to analyse their engineering behaviour is to use a geotechnical approach with the sludge being considered as a fine-grained soil with a high organic matter content (Sarsby, 2001).

2. SEWAGE SLUDGE

Sewage generally consists of domestic wastewater and industrial effluents and contains approximately 1000mg/litre of impurities of which between about 67% and 75% are organic and degradable material. The organic substances present include carbohydrates, lignins (complex compounds of carbon, hydrogen and oxygen), fats, soaps and synthetic detergents, and proteins. The solid portion contains paper fibres, fine soil particles, glass and metal fragments. Generally the more industrialised a community is, the greater the probability that heavy metals and persistent organics will be present in significant quantities – typical contamination values are given in Table 1. This contamination prevents the spreading of treated sewage sludge on agricultural land and hence a growing quantity is being disposed of as landfill.

Table 1: Contaminants in sewage sludge

Contaminant	Concentration (mg/kg)	
	Range	Median
Cadmium	0.4 - 3300	about 20
Chromium	10 - 30000	about 700
Copper	50 - 15000	about 700
Iron	15 - 20000	about 550
Lead	80 - 30000	about 500
Zinc	50 - 30000	about 2000
Benzene	up to 600	/
Toluene	up to 130	/
Xylene	up to 1000	/
Phenol	up to100	/

Although the moisture content and bulk density values (typical data are included in Table 2) are very different from those for materials normally encountered in geotechnical engineering they are not unique and peat deposits often have higher moisture contents and lower bulk densities. However, the low specific gravity of peat fibres means that they occupy a significant volume of a sample and form a mat whereas sewage sludge exists as a 'jelly' with negligible shear strength. Although the sludge behaves like a gel the solid component consists mainly of sand-sized particles. Unfortunately each solid particle is surrounded by a 'cellular biomass' which is linked to a particle by a series of calcium bridges. These bridges create an entire 'embraced mass' effect and cause the solid particles to be held in suspension. The 'cellular biomass' is a thick poly-saccharide liquor which behaves in a viscous manner and tends to restrict flow in between the sludge particles.

Table 2: Properties of common sludges

Source	Moisture Content (%)	Liquid limit	Plastic limit	Organic Content (%)	Dry solids content (%)
Sewage: dewatered	120-160	130-175	50-65	20-40	10-20
lagooned	400-900	"	"	"	≈5
Dredging	70-130	≈150	≈50	≈20	10-35
Papermills	60-300	150-170	40-240	40-80	5-40
Water treatment	≈700	≈600	≈200	/	≈10

3. LABORATORY INVESTIGATION

An extensive laboratory investigation has been undertaken into the consolidation and shear strength characteristics of sewage sludge from a typical lagoon. The material behaviour has been investigated using consolidation cells, laboratory vane apparatus and triaxial apparatus.

The consolidation tests were undertaken in 254 mm diameter, hydraulic oedometers (Rowe Cells) for both vertical and horizontal drainage. Pore pressures were measured in some tests. The tests with vertical water flow utilised top drains whilst for horizontal flow a central sand drain (12 mm diameter) was incorporated to permit radial inwards drainage. After each increment of vertical stress had been applied the sludge was left to drain until primary consolidation was complete and continuing volume decrease was due to secondary compression alone. At this stage the oedometer was opened and the shear strength of the consolidated mass was measured using a laboratory vane. The moisture content of the consolidated sludge was determined at the same time. The apparatus was then reassembled and further pressure increments were applied in the same way. Triaxial samples were extracted from some oedometer specimens and were subjected to quick undrained triaxial compression (with and without pore pressure measurement).

4. CONSOLIDATION BEHAVIOUR

The settlement-time curves from consolidation tests had the same form as curves for highly-organic soils. However, the sludge exhibited very low values of Cv when compared to organic soils or even clays - C_v values of 0.1 to 0.7m^2/yr were obtained at low effective stresses (1to 5kN/m2). There was a noticeable decrease in C_v as the vertical effective stress was increased, becoming as low as 0.02m^2/yr for a consolidation pressure of 30kN/m^2. Two factors seem to be responsible for the low consolidation rates - the composition/viscosity of the pore fluid (more akin to a gel than water) and the ongoing digestion of the sludge and generation of gas bubbles.

The coefficient of consolidation with respect to horizontal drainage, although significantly larger than C_v (with C_h/C_v ranging from 8 to 22), was very low for material with such a very high moisture content and a low solids content.

Using the equation $k = C_v.m_v\gamma_w$ the permebility of the sludge was estimated to vary between 0.1 x 10^{-7} m/s and 0.2 x 10^{-9} m/s. Since the consolidation behaviour of the sludge violates many of the assumptions made in the derivation of Tarzaghi's consolidation theory the coefficient of vertical permeability of one fully consolidated sample (vertical stress of 4.9 kN/m^2) was measured directly. A constant water head was applied to the top drain and the outflow rate from the bottom drain was measured over a period of 3 weeks. The measured coefficient of vertical permeability was 0.8 x 10^{-9} m/s as compared to the calculated average values of 2.0 x 10^{-9} m/s and 1.2 x 10^{-9} m/s for consolidation pressures of 4.9 and 7.4kN/m^2 respectively. This value confirmed that the low permeability of the material was directlyresponsible for the poor drainage properties of the sludge.

The sludge exhibited large volume reduction (around 25% vertical strain for a pressure increment of 1-10kN/m^2) during consolidation. It was found that the consolidation settlement could be represented by the form of equation used for a normally-consolidated clay with C_c values in the range 10.0 to 1.5 (decreasing with effective stress level). If, on the other hand, the compression was expressed in terms of the coefficient of volume compressibility the resultant m_v values are very large but are in keeping with typical values for peats and organic clays at similar moisture contents.

Despite the highly-viscous nature of the pore fluid in the sludge the material exhibited little creep. The Coefficient of secondary compression (C_α) was around 0.02 to 0.04. However, the low C_α values may result from the very long time required for primary consolidation to be completed.

5. SHEAR STRENGTH

The high water content of the 'natural' sludge meant that it exhibited very low shear strength (of the order of 1 to 3kN/m^2). There was a significant increase of shear strength with consolidation, although the actual values remained low in terms of the shear strengths normally associated with soils. The shear strength of a wide range of wastewater sludges can be represented accurately by an empirical equation (Voss, 1993; Sarsby, 2000) of the form

$$c_u = Ae^{B\rho} \tag{1}$$

where e is the voids ratio, ρ is the bulk density, A and B are constants which depend on the type of sludge. Bulk density is considered a better indicator of the likely shear strength behaviour of a sludge than just water content or fibre:solids ratio. This is because bulk density encompasses the effects of both voids ratio (the pore fluid has zero shear strength) and fire/solids content (the fibres will provide little frictional shear strength). For such high water content materials ϕ_u is always zero. For the sewage sludge tested by the Author A was 2x10^{-8} and B was 17.5 for bulk densities defined in units of Mg/m^3.

Interestingly, for all consolidation pressures, i.e. from the insitu conditions upto 30kN/m^2 (laboratory maximum), the ratio of the undrained shear strength to the effective overburden pressure was in the range 0.66 to 0.79. This range of values seems to be very different from those predicted by Skempton's equation relating undrained strength to effective overburden. However, when it is considered that sewage sludges exhibit Plasticity Indexes in the range 80 to 125 approximately (because of their fibre content) then Skempton's equation predicts values in the range 0.41 to 0.57 approximately.

A large range of values was obtained for the effective friction angle of sludge - 2.5 to 35^0. This was probably due to the very low values of effective stress at which the tests were conducted. Small inaccuracies in the measured values of pore pressure (and gas production due to fibre decomposition was a problem) caused large changes in the assessed values of effective stress. Even though sewage sludge is highly fibrous the material had low tensile strength - effective cohesion was in the range 0 to 10kN/m^2.

Table 3: Chemical additives and performance

Additive	Function or specific property	Effect on sludge
Dilute Sulphuric Acid	pH adjustment to destabilise any toxic content. The acid will have a dehydrating effect on organic matter.	Surface of the sludge became dehydrated, sludge became stiffer. No water was expelled.
Sodium Carbonate	pH adjustment	Small amount of sedimentation. Some free water coming to the surface.
Sodium Chloride		No effect
Sodium Hexameta-phosphate	To reduce surface tension effects. To act as a degreasing agent to reduce the resistance between particles.	Sludge became very fluid. No sedimentation. No water expelled.
Aluminium Potassium Sulphate.	Act as a coagulating agent	No effect
Calcium Carbonate	pH adjustment and a flocculant to aid sedimentation	Slight amount of sedimentation
Lenetol	Wetting agent, reduces surface tension	Sludge became very fluid. No sedimentation.
Ethylene Diamine Tetra Acetic Acid (EDTA)	To remove metals. To breakdown the calcium bonds in the cellular biomass	Significant sedimentation. Much free water appeared on the surface of the sludge

6. MATERIAL IMPROVEMENT

The consolidation tests showed clearly that if the sludge permeability could be improved then dewatering of the material would be facilitated. Because of the low solids content of the sludge it would appear that the low permeability results from either the viscosity of the pore fluid (which was not readily apparent from visual inspection of the flow behaviour of expelled pore fluid) or some form of chemical bonding or biological coagulation involving the fluid and the fibres. Consequently it was decided to try to change the structure of the sludge, and possibly the viscosity of the pore fluid, using chemical additives. Observation of various methods of dewatering such wastes during the sewage treatment process suggested that adjustment of sludge acidity (by the addition of a polyelectrolyte or coagulating agent) might break down the molecular bonding between the solid particles. This would then permit more efficient separation of solids and water. Accordingly several chemicals were selected for preliminary tests. Two dosages (2%% and 5% by weight of the mass) thoroughly mixed with sludge samples which were left for several weeks for observation. The chemical additions, and their performance are listed in Table 3.

Only Ethylene Diamine Tetra Acetic Acid (EDTA) had any significant effect on the sludge in that the coarser particles settled out and free pore fluid appeared on the surface of the material. Control samples of untreated sludge, which were left to stand over the same period of time, exhibited essentially no settling. In both cases the consistency of the sludge remained that of a gel. To see if the EDTA had a beneficial effect on the drainage characteristics of the sludge a sample was mixed with the additive and then consolidated in a Rowe Cell (with vertical drainage) under pressure of 4.9 kN/m^2. The result was disappointing in that the measured C_v value was only 0.16 m^2/yr, i.e. approximately twice the value obtained for untreated sludge. When the consolidation pressure was subsequently raised to 9.8kN/m^2 the material would only consolidate very slowly. It would appear that the EDTA did break down the molecular structure of the sludge as it was observed fluid expelled was a thick, resinous, liquid. This liquid stained the pyrex flask in which it was collected and became quite 'tacky' when left exposed to the atmosphere. The pore fluid expelled was thus a mixture of the free water within the sludge and the sugar-based polysaccharide contained in the biomass, hence .its resinous nature and tendency to clog the drainage discs - which probably lead to significant under-estimation of C_v.

7. SUMMARY AND CONCLUSIONS

The shear strength of wastewater sludge can be defined in terms of effective stress parameters although measured parameters cover a wide range of values. A more convenient and reliable prediction of shear strength is obtained using total stress parameters and an empirical equation has been derived for this purpose.

The settlement at full consolidation can be represented by the form of equation used for a normally-consolidated soil with C_c values in the range 10.0 to 1.5 (decreasing with effective stress level).

Of the several additives that were mixed with sewage sludge only one produced a noticeable difference in the sedimentation behaviour of the material. However, even this additive did not improve the drainage characteristics of the sludge.

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