Cracking in clay – data report on cracking of clay beams by 4-point beam tests

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1 Introduction

Liner systems of a landfill perform the vital task of retaining the leachate produced by the waste. A clay liner, with its characteristic very low permeability, has been the common form of liner since the early days of landfill construction. Even though newer landfills have well engineered composite liner systems with Geo-synthetic clay (GSC) liners, clay liners are still commonly used in many countries of the world.

The low permeability of clay is the main property that makes it ideal for landfill liner construction. The presence of cracks in clay impairs the main function of a clay liner. Cracking in clay can be caused by many factors such as freezing and thawing, desiccation, shrinkage and differential settlement (Fig. 1). The mass strength of the clay in liners, foundations, embankments and slopes can be adversely affected by cracks in the clay. Cracks provide a preferential flow path to fluids, thus increasing the hydraulic conductivity many fold. Understanding the criteria for tensile crack initiation would enable us to better design and manage clay foundations, embankments, slopes, dams and liners.



Fig. 1 Clay liner cracking (Environment Agency, R&D Technical Report P1-385/TR1Source).

Differential settlement of the landfill foundation can induce tension cracks in the clay liner. Fig. 1 shows such tension cracks in the clay liner in a schematic cross section of a landfill. These tension cracks can be difficult to observe in a landfill as they are below the waste fills and could cause leachate leakage and hence ground water pollution. Understanding the cracking phenomenon in clay is essential not only for landfill liners but also for other common facilities such as embankments and dams whose performs depend on the strength and permeability of clay. This chapter presents an investigation into the stress-strain criteria for cracking in clays by performing 4-point bending tests on consolidated kaolin clay beams (Thusyanthan et al. 2005e). The clay beams were obtained from specimens of kaolin clay one dimensionally normally consolidated to a stress of 500 kPa or 250 kPa. Load controlled and strain controlled tests were performed on clay beams with varying initial suction to understand the stress-strain criteria for crack initiation in clay. Tensile strain to cracking was measured by performing PIV analysis (White et al. 2003) on the digital images of the beams being subjected to bending, while the suction was measured by pore pressure and tension transducers (PPTTs) installed at three different locations within the beams.

Clay beams could have been formed from compacted clay; however the variability present in the compacted clay would make comparing the results of different beams difficult. Furthermore, compacted clay beams would invariably have some weak layering which may vary from beam to beam; hence the failure stress may be unique to each beam.

2 Experimental setup

2.1.1 Specimen preparation

Load controlled and strain controlled 4-point bending tests were carried out on beams trimmed from E-grade kaolin clay which had been one-dimensionally consolidated either to 500 kPa (type-A beams) or to 250 kPa (type-B beams).

E-grade kaolin clay powder was thoroughly mixed with an equal mass of water under vacuum to produce a slurry. The kaolin slurry at 100% water content was then one-dimensionally consolidated to an effective stress of 500 kPa or 250 kPa in a consolidation rig (Fig. 2(a)). Beams 320 mm long (transverse to the consolidation loading) and of 80 mm cross-section, weighing 4 kg, were cut from the consolidated clay specimens (Fig. 2(b)). All beams were wrapped in polythene and stored in air-tight containers prior to testing. The E-grade kaolin clay has a liquid limit of 51% a plastic limit of 30% and permeability of the order of 10⁻⁹ m/s (Barker, 1998). The values of critical state parameters of E-grade kaolin clay from various sources were summarised in section 3.5.2 in chapter 3- Thusyanthan 2005, Ph.D Thesis, University of Cambridge.



Fig. 2 Kaolin clay : (a) Consolidated clay specimen; (b) 320 mm × 80 mm × 80 mm clay beam.

2.1.2 Installation of PPTTs into the clay beams

Prior to testing a beam, it was removed from the air-tight container and three PPTTs (one near the compression face, one near the tension face and the other in the middle of the beam) were installed at the mid-length of the beam by slowly drilling from one end of the beam. The PPTTs were saturated under vacuum prior to installation. The details of the saturation process are described in Take and Bolton (2003). Fig. 3(a) shows the location of PPTTs in the clay beam. A wooden framework and an aluminium guide were used to ensure that the drilling alignment and depth were correct (Fig. 3(b)) with the beam protected against evaporation by a polythene cover. The PPTTs were installed on a diagonal of the cross section of the beam in an attempt to mitigate their tendency to weaken the cross-section. The PPTTs were inserted into the drilled holes, back filled with clay slurry and allowed to set (Fig. 3(c)). After the installation of PPTTs, the pore pressure was monitored to ensure that it was uniform before the polythene cover was removed. The elevation face of the beam which would face the digital camera was dusted with dyed fine sand. This gives the surface some texture which is required for good PIV analysis of the beam images.





3 Testing procedure

(b)

allowed to set.

All the beams initially registered suction in the range 15 kPa to 30 kPa after the equilibration of PPTTs. This suction increased slowly as the beams were allowed to air dry for different periods to obtain various values of initial suction. An air fan was used to speed up the drying process for beams requiring high suction for testing. Beams were rotated at regular intervals to facilitate uniform drying from all sides. This was confirmed by the uniform readings of the PPTTs. Fig. 4 shows the PPTT readings during installation, setting of back filled clay and drying. The spikes in the PPTT readings during installation were caused when the PPTT reached the end of the drilled hole and got pressed again the clay while the spikes during setting and drying was caused when rotating the beam. Load-controlled and strain-controlled bending tests were performed on the beams with various initial suctions. 30 mm diameter

(c)

Fig. 3 Preparation of clay beams: (a) PPT location; (b) Drilling into clay beam; (c) PPTs installed and

perspex rods were used to apply load to the clay beams in the direction of their initial onedimensional consolidation. Table 3.1 summarises the tests carried out.



Fig. 4 PPT reading during and after installation of PPTTs into the clay beam.

Type of 4 point	Test	Initial suction	Pore pressure	Success
bending tests		measured (kPa)	measurement	of PIV
			during test	analysis
Load controlled tests	AL15	15	Good	Good
on clay type-A beams.	AL45	45	Good	Good
(2kg every 3 min.)	AL75	75	Good	Good
	AS25	25	Good	Good
	AS45	45	Good	Good
Strain controlled tests	AS62	62	Faulty PPT	Good
on clay type-A beams	AS75	75	Faulty PPT	Good
	AS82	82	Faulty PPT	Poor
	AS80	80	Good	Good
	AS100	100	Good	Good
	AS102	102	Good	Good
	BS15	15	Good	Good
Strain controlled tests	BS22	22	Good	Good
on clay type-B beams	BS45	45	Good	Good
	BS46	46	Good	Poor
	BS65	65	Good	Good
	BS92	92	Good	Good

type-A beam is from 500 kPa consolidated clay specimen type-B beam is from 250 kPa consolidated clay specimen

Load-controlled tests were carried out on 3 beams of type-A using the set up shown in Fig. 5(a). A step load of 20 N was applied to the beam at intervals of 180s by allowing 2 kg of water to flow into the bucket attached to the framework. Fig. 5(b) shows the set-up used in strain-controlled tests. A motorised actuator was used to apply the load on the beam at a uniform displacement rate of 0.23 mm/min. Pore pressure readings from all 3 PPTTs were recorded throughout the tests.

Two digital cameras were mounted facing the beams, one to capture the central region of the beam and the other to capture the entire beam, as the beam was subjected to bending. The digital images were captured every 10 s during the test. These images were used in particle image velocimetry (PIV) analysis (White et al. 2003) to obtain the displacement vectors in the beam. A thin glass sheet, with a grid of black markers at known locations, was positioned very close to the beam. These markers acted as control targets to normalise the PIV analysis.



(a)



Fig. 5 (a) Setup for load controlled test; (b) setup for stain controlled test.

3.1.1 PIV analysis

The experimental investigation of cracking described in this paper concentrates on the stressstrain behaviour of the mid-span of the beam where the bending moment was uniform at its maximum value. The evolution of the magnitude and distribution of the longitudinal bending strain, ε_{zz} , at this location was precisely measured using the non-contact digital image correlation technique of Particle Image Velocimetry (PIV). This technique is described by White et al. (2003) and Take (2003) and allows the precise determination of soil displacements though a series of digital images without resorting to predefined target markers, instead operating on the visual image texture of the soil (colour, grain orientation, etc.) In this application, the grain size of the soil, E-grade Kaolin, ensured that the natural texture of the material could only be seen at the microscopic level. Thus, using the technique described by Take (2003), an artificial texture was applied to the elevation face of the beam using with dyed fine sand. As shown in Fig. 6(a), the resulting image texture is a high contrast black and white random pattern ideal for PIV analysis.

As PIV operates on image texture rather than pre-defined target markers, the displacement of any location throughout the beam could be measured. In this application, 33 pairs of 32x32 pixel measurement patches were defined in the digital image on either side of the mid-span of the beam throughout the full height (Fig. 6(a)). Thus, these pairs of displacement nodes can be thought of as thirty-three virtual strain gauges and can be used to calculate the longitudinal strains throughout the depth of the beam by dividing the horizontal movement of the two patches making up each pair by the original distance between the patches (Fig. 6(b)).

Digital images of the beams were captured every 10s during flexural testing by two 4 Megapixel digital cameras: one focussed on a wide field of view to observe the behaviour of the entire beam (Fig. 7)and the other zoomed to capture the detailed behaviour of the mid-span (Fig. 6(a)). As shown in Fig. 6(a), a thin glass sheet containing a grid of black control makers at known locations was placed in front of the beam to provide a reference coordinate system visible in both cameras. This coordinate system was then used to improve the precision of the measured strains using photogrammetric camera calibration to remove camera errors such as the variation in scale factor due to imperfect camera positioning, radial and tangential lens distortion, and refraction (White et al., 2003).



(b)

Fig. 6 (a) View from camera 1 and 32×32 pixel size patches used in PIV analysis; (b) strain calculation from the patch movement



Fig. 7 Images from camera 2



4 Results

All the beams failed by tension cracking near the mid-span of the beam. The load and hence the bending moment experienced by the beams increased up to the onset of cracking. After the initiation of a tension crack the load decreased and the crack grew through the beams. Complete collapse of the beams was observed once the crack had propagated through about two thirds of the beam thickness.

References

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- 2. White D.J., Take W.A. & Bolton M.D. (2003). Soil deformation measurement using particle image velocimetry (PIV) and photogrammetry. *Géotechnique* 53, No. 7, pp. 619-631.

4.1.1 Beam AL15



4.1.2 AL45



4.1.3 AL75



4.1.4 AS45



4.1.5 AS80

(every 50s)



4.1.6 AS62



4.1.7 AS75



4.1.8 AS80



4.1.9 AS102





4.1.10 AS100



4.1.11 AS25



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4.1.12 BS22



4.1.13 BS46





4.1.14 BS92



4.1.15 BS65



Cracking in clay – data report on cracking of clay beams by 4-point beam tests

4.1.16 BS45



4.1.17 BS15



5 Beam picture at the start of the test and at the initiation of crack

AL15

At the start of the test



At initiation of crack



AL45

At the start of the test



At initiation of crack



AL75

At the start of the test



At initiation of crack



AS45

At the start of the test



At initiation of crack



AS82

At the start of the test



At initiation of crack



AS62

At the start of the test



At initiation of crack



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AS75

At the start of the test



At initiation of crack



AS80

At the start of the test



AS102

At the start of the test



At initiation of crack



At initiation of crack



AS100

At the start of the test



At initiation of crack



AS25

At the start of the test



At initiation of crack



BS22

At the start of the test







BS46

At the start of the test



At initiation of crack



BS92

At the start of the test



At initiation of crack



BS65

At the start of the test



At initiation of crack



BS16

At the start of the test



At initiation of crack



BS15

At the start of the test



At initiation of crack

