Centrifuge modelling of the initiation of cracks in a clay liner subjected to differential settlement with and without overburden pressure

Modélisation centrifugeuse des débuts de fissuration dans un revêtement d'argile sujet à un tassement différentiel, avec et sans pression de surcharge

Talia S. da Silva, Mohammed, Z.E.B. Elshafie, Gopal, S.P. Madabhushi
Department of Engineering, University of Cambridge, United Kingdom, tsd30@cam.ac.uk

ABSTRACT: Compacted clay liners are used in the basal and capping layers of landfills to separate the waste material from the environment. These liners are subjected to differential settlement through degradation of the waste or compression of the subgrade. This differential settlement induces cracking in the liner, and reduces the effectiveness of the clay as an environmental protection barrier. Physical model tests were conducted in the geotechnical centrifuge to study the influence of differential settlement on clay liners and observe the crack mechanism using a consolidated kaolin clay to model the clay liner. Differential settlement was imposed on the clay beam by means of a trapdoor. Cracking in the clay was monitored through digital analysis of images taken as the tests were conducted using particle image velocimetry. The test investigated the orientation and types of cracks formed with varying void dimensions and with and without overburden pressure. The unconfined clay over the small trapdoor was able to support itself across the void; a punching shear failure occurred in the case of a wider trapdoor or greater overburden pres sure.

RÉSUMÉ : Des revêtements d'argile compactée sont utilisés pour les couches inférieures et supérieures des décharges afin de séparer les déchets de l'environnement. Ces revêtements sont sujets à un tassement différentiel pendant la dégradation des déchets ou la compression du sol. Ce tassement différentiel a pour conséquence des fissures dans le revêtement, et réduit l'efficacité de l'action de l'argile en tant que barrière de protection environnementale. Des tests impliquant des modèles physiques ont été effectués dans la centrifugeuse géotechnique afin d'étudier l'influence des différences de tassement sur les revêtements en argile et d'observer les mécanismes de fissuration, en utilisant un faisceau d'argile de kaolin consolidé modélisant le revêtement d'argile. Un tassement différentiel a été appliqué sur le faisceau d'argile au moyen d'une trappe. Les fissures dans l'argile ont été suivies grâce à l'analyse digitale d'images prises pendant les tests, en utilisant la vélocimétrie d'image de particules. Le test a étudié l'orientation et les types de fissures formées avec des dimensions de vides variables ainsi qu'avec et sans pression de surcharge. L'argile non confinée au-dessus de la petite trappe a pu se maintenir en travers du vide; une rupture par cisaillement et poinçonnement s'est produite dans le cas d'une plus trappe plus grande ou d'une pression de surcharge plus importante.

KEYWORDS: cracking, compacted clay liner, centrifuge, particle image velocimetry (PIV)

1 INTRODUCTION

Compacted clay liners (CCLs) are used in the basal and capping layers of landfills to separate the waste material from the environment. As the waste is highly heterogeneous and compressible, these liners are subjected to differential settlement through degradation of the waste or compression of the subgrade. In the construction of piggyback landfills where a new landfill liner is constructed above an existing waste deposit, the clay liner is subjected to the formation of voids or differential settlement due to the compression of waste underneath.

Differential settlement induces cracking in the liner; this cracking results in a loss of integrity of the liner, and reduces the effectiveness of the clay as an environmental protection barrier. (Thusyanthan et al., 2007).

Physical model tests were conducted to study the influence of differential settlement on clay liners. A layer of consolidated kaolin clay was used to model the compacted clay liner. The tests were conducted in the geotechnical centrifuge at the University of Cambridge at an acceleration of 40 g.

Increasing differential settlement was imposed on the clay beam by means of a settling trapdoor; this simulates the formation of a void beneath the CCL with a vertical discontinuity. Cracking in the clay was monitored through digital analysis of images taken as the trapdoor was lowered, which were analysed using particle image velocimetry (PIV).

The test series aimed to investigate and identify the onset of cracking in the clay, and observe the size, location and types of cracks formed. The influence of an overburden pressure on the crack initiation and orientation was also investigated.

2 EXPERIMENTAL METHODOLOGY

2 .1 *Clay preparation*

In order to achieve a homogeneous model material representative of a CCL and able to be analysed with known material and mechanical properties, a strip of one-dimensionally consolidated speswhite kaolin clay was used in the model instead of compacted material as is used in the field. This is as used by Thusyanthan (2005) in the study of the behaviour of cracking in clay beams, and Jessberger and Stone (1991) in the investigation of subsidence effects on clay liners. The material properties of the clay as reported by Williamson (2014) are shown in Table 1. Thusyanthan (2005) details how the model CCL has the same material properties, i.e. plasticity, particle size distribution and moisture content, as would be required for a CCL constructed in practice.

For the model liner preparation, the powdered clay was mixed to an initial moisture content of 120% under vacuum. The slurry was one dimensionally consolidated in stages to a final vertical effective stress of 500 kPa, and then unloaded incrementally in stages of 80 kPa to prevent air-entry and ensure that it remained fully saturated. A final suction of 60 kPa was maintained on the clay to ensure that the clay had sufficient stiffness that it was able to be handled in the preparation of the CCL specimens.

For the reported tests, two sets of clay consolidations were conducted. Three liner samples were prepared from the first batch, and one from the second. The initial and final moisture content (MC) of the batches are also shown in Table 1, as well as an estimate of the one dimensional consolidation parameters for the second batch which compare well to the literature values.

Table 1. Speswhite Kaolin properties

Parameter	*Williamson, (2014)*	*Slurry Batch 1*	*Slurry Batch 2*
G_S	2.61		
Plasticity Index, I_P	32		
Internal angle of friction, Φ (°)	23		
N_λ	3.2642		
Slope of normal compression line, λ	0.1837	-	0.222
Slope of unload- reload line, κ	0.0469	-	0.0388
Coefficient of consolidation, c_v (mm^2/s)		-	0.32
Initial MC (%)		127.53	126.56
Final MC (%)		46.53	46.40

A 25 mm thick model clay liner was prepared in order to model a 1 m thick prototype CCL at 40 g in the centrifuge; this is the same as used in the studies by Thusyanthan (2005). The liner was cut from the consolidated block and trimmed to the final height using steel angles as guides; the process of the liner preparation is shown in Figure 1. The surfaces of the prepared specimens were sprayed with a thin film of silicone coating prevent them drying out during the model preparation and testing.

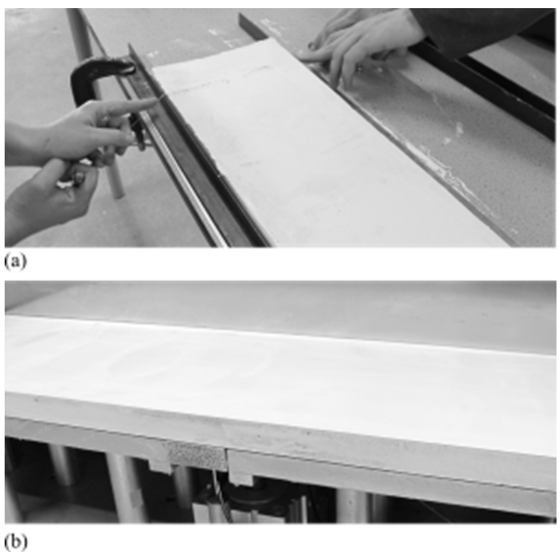

Figure 1. Preparation of the clay liner (a) Trimming to thickness of 25 mm using steel guides and wire once clay has been removed from consolidometer block (b) Placement of the model liner in the test apparatus.

2 .2 Centrifuge modelling

The physical model tests were conducted in the 10 m balanced beam geotechnical centrifuge at the University of Cambridge (Schofield, 1980) at an acceleration of 40 g. Tests were conducted in a rectangular container of plan dimensions of 200 mm × 790 mm; this is the same container that the clay was consolidated in to ensure that the prepared liner fit the width of the box. Plane-strain testing with the inclusion of a transparent boundary was chosen for the ability to obtain optical measurement of the clay deformation and the overburden soil displacements using Particle Image Velocimetry (PIV) (Stanier et al., 2015).

A rectangular trapdoor of variable width, either 50 or 100 mm was used to simulate the formation of a small void beneath the soil; this is equivalent to a 2 m or 4 m prototype width void respectively. The trapdoor is connected to a hydraulic piston, which is connected to a second piston outside the box (closed system). The displacement is controlled via a linear actuator fitted to the external piston: the upwards movement of the linear actuator results in downwards movement of the trapdoor. The trapdoor was lowered continuously at a rate of 0.17 mm/min; a sequence of images was taken throughout this process.

An annotated photograph of the centrifuge package and trapdoor mechanism is shown in Figure 2.

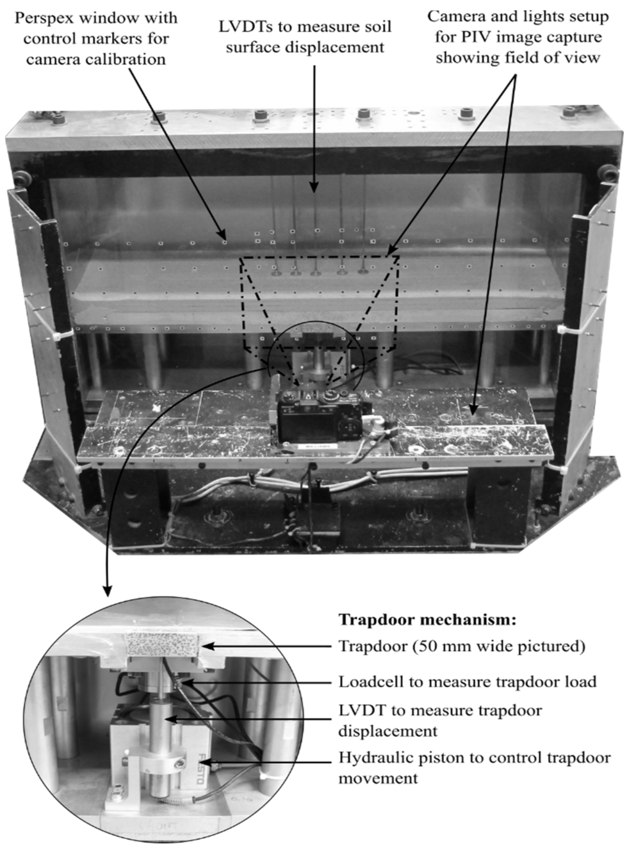

Figure 2. Plane-Strain centrifuge package with transparent Perspex window for image capture of soil displacements and trapdoor for the simulation of void formation.

2 .3 Test procedure

A series of four tests were conducted to investigate the deformation and cracking in the clay when subjected to the differential settlement imposed by the trapdoor. A test was conducted with an unconfined clay layer, and subsequently with a confined clay layer with an overburden of soil equivalent to the clay height (25 mm, ~16 kPa). This is equivalent to the overburden pressure that a capping CCL would experience. The tests were repeated for a trapdoor width of 50 mm, and 100 mm. A summary of the tests conducted is shown in Table 2; this allows a matrix of comparison based on either trapdoor width or presence of confining pressure.

Dry Hostun sand was used for the soil overburden; this was prepared at a minimum target relative density of 85 % by using air pluviation with an automatic sand pourer as described by (Zhao et al., 2006).

Table 2. Centrifuge test series

Name	Test ID	*Trapdoor width (mm)*	*Overburden depth (mm)*	*Clay batch*
50 – UNC	CCL01	50	0	1
50 – CON	CCL06	50	25	2
100 – UNC	CCL02	100	0	1
100 – CON	CCL03	100	25	1

2.4 Moisture content and shear strength estimate

The moisture content (MC) of the clay liner was measured before and after the centrifuge test was conducted; the results are shown in Table 3. The average MC was used to calculate the density, (γ) of the clay liner, assuming that it remains fully saturated.

The vertical stress (σ_v) acting on the clay was calculated from the overburden pressure and self-weight of the clay. The pore water pressure (PWP) distribution was assumed to be a hydrostatic distribution, in combination with the assumed initial suction. Due to the thickness of the clay liner, this was not able to be accurately measured with pore water pressure transducers. The stress distributions and vertical effective stress ($\sigma_{v,eff}$) are shown in Figure 3 for the unconfined clay layer. For the confined clay layer, σ_v and $\sigma_{v,eff}$ (Figure 3(a) and (c) respectively) would be translated by the value of the overburden pressure.

The undrained shear strength, c_u, was estimated from the relationship proposed by Muir Wood (1990) based on the vertical effective stress acting on the clay and the overconsolidation ratio (OCR), shown in the set of equations below. The drained shear strength, τ, is estimated based on the Mohr-Coulomb equation. The results of the calculations for the clay used in the tests are shown in Table 3.

$$\frac{c_u}{\sigma_v} = \left[\frac{c_u}{\sigma_v}\right]_{nc} OCR^{\Lambda}; \quad \left[\frac{c_u}{\sigma_v}\right]_{nc} = 0.11 + 0.37\ I_P; \quad \Lambda = \frac{\lambda-\kappa}{\lambda}$$

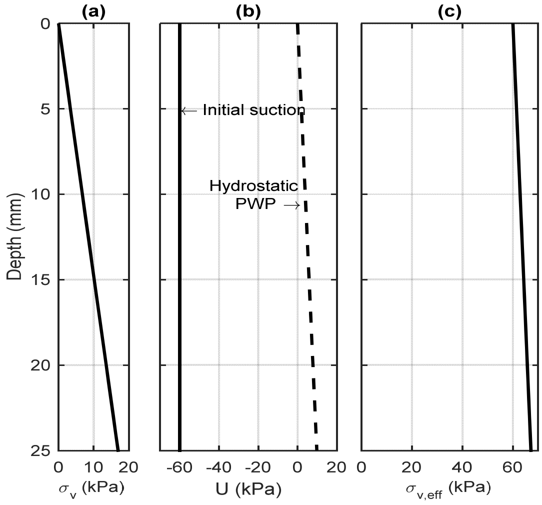

Figure 3. Stress profiles in the clay layer at 40 g with no overburden pressure showing (a) total vertical stress (σ_v), (b) initial suction and hydrostatic PWP, and (c) vertical effective stress ($\sigma_{v,eff}$)

Table 3. Moisture and strength parameters of model CCLs

Name	MC_i	MC_f	γ	*Ave.* σ_v	*Ave. OCR*	c_u	τ
	%	*%*	*kN/m³*	*kPa*	-	*kPa*	*kPa*
50-UNC	46.5	46.7	16.93	63.6	7.9	67.5	27.0
50-CON	45.6	47.7	16.93	79.6	6.3	71.5	33.8
100-UNC	46.2	45.2	17.01	63.6	7.9	67.5	27.0
100-CON	46.6	48.4	16.86	79.5	6.3	71.5	33.8

3 RESULTS & DISCUSSION

The photographs taken of the tests showing the cracking and deformation in the clay liner and overburden soil are shown in Figure 5 at a nominal trapdoor displacement of 5 mm. This was chosen as by this point the cracks in the clay are fully developed. Observations from the photographs show that the unconfined clay over the 50 mm trapdoor was fully able to support itself across the void; no visible cracking nor strain localisations in the PIV were observed in the CCL. Although the clay was able to support itself over a void with no overburden pressure, the presence of even a small amount of additional loading was enough to cause a complete failure of the clay liner. The arching ability of the clay on its own cannot be relied upon to provide any support if there is a change in loading.

In the other three tests conducted, shear cracks were observed throughout the depth of the clay layer. The overburden pressure creates a more prominent punching failure in the clay with cracks at a more vertical orientation than when no overburden is included (comparing ‘100–UNC’ and ‘100–CON’). The observed shear crack orientation is summarised in Table 4 for comparison. The PIV result for test 50-CON where a difference in shear crack orientation was observed is included in Figure 4. The approximate displacement at which visible cracks are initiated at the discontinuity and complete failure of the clay is observed is also recorded in the table: this is the point at which the crack is observable at the surface of the clay layer.

Table 4. Shear crack orientation

Name	*Shear crack orientation to vertical, at 5 mm disp. (°)*	*Crack initiation*	*Failure*

	Left	*Right*	*disp. (mm)*	*disp. (mm)*
50-CON	6*	23	2.1	3.1
100-UNC	19	18	2.9	4.7
100-CON	6	10	2.4	4.1

* A strain localisation at an orientation of 18° is observed in the PIV prior to the formation of the visible crack (see Fig. 4)

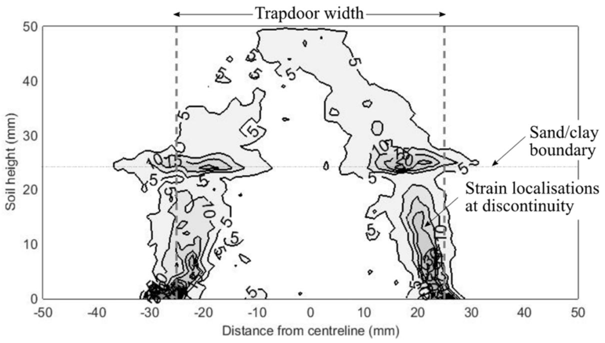

Figure 4. 50-CON PIV result showing shear strain localisations at 0.85 mm trapdoor displacement.

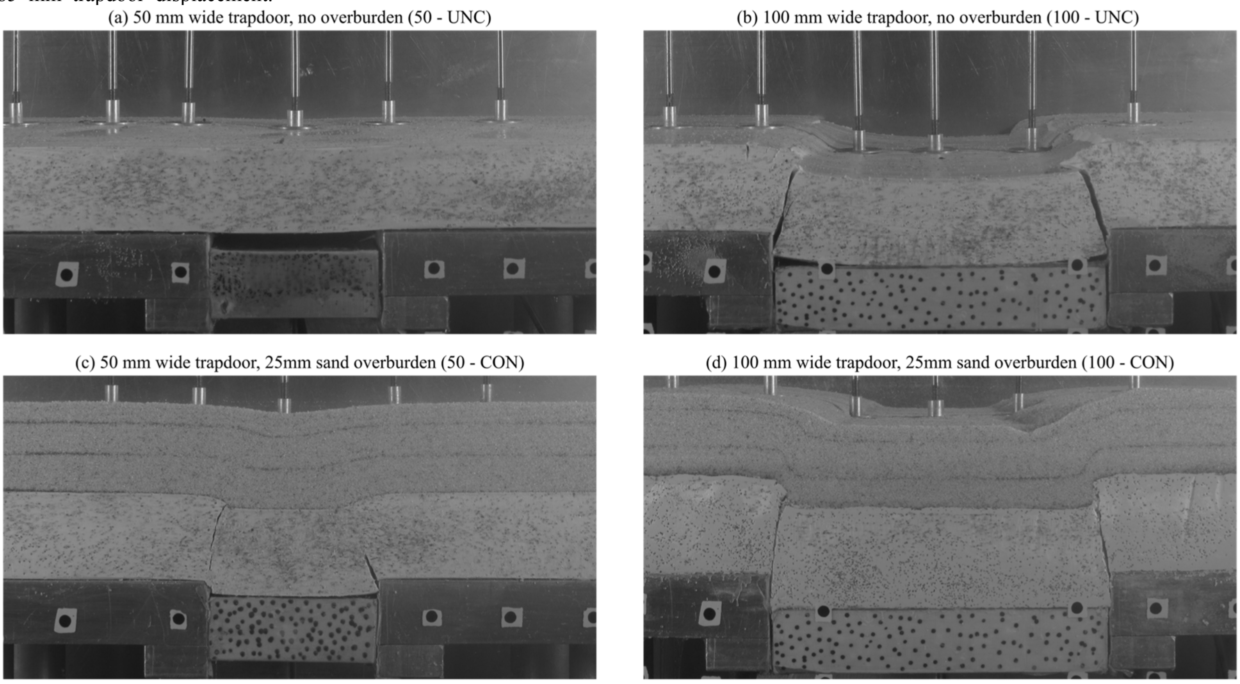

Figure 5. Deformation and cracking in the CCL above the void

In order to describe the potential differences between the tests, an estimate of the shear resistance across the clay liner in comparison to the maximum potential shear loading from the clay self-weight across the void and overburden load is made in Table 5. The loading rate is closer to a drained behaviour of the clay. The drainage time assuming full consolidation and double drainage in the clay liner is 16 minutes. The results show that in the cases where failure occurred, the load is approximately equal to or greater than the resistance. The failure mode was brittle, and little necking or bending of the clay was observed as reported by Richards and Powrie (2011).

Table 5. Shear resistance and loading at discontinuity

Name	*Undrained shear resistance (kN/m)*	*Drained shear resistance (kN/m)*	*Max. shear load (kN/m)*
50-UNC	67.5	27.0	16.93
50-CON	71.5	33.8	32.93
100-UNC	67.5	27.0	34.02
100-CON	71.5	33.8	65.73

4 CONCLUSIONS & FURTHER RESEARCH

The behaviour of a model compacted clay liner over a void was observed in a series of centrifuge tests conducted with a variation in trapdoor width and confining pressure on the clay surface. The results showed a drained behaviour of the clay gave a closer prediction of the shear capacity of the clay. Displacement discontinuity results in the formation of a punching shear failure in the compacted clay liner in the case of a wider trapdoor or greater overburden pressure. The presence of the confining stress was not sufficient to induce ductile behaviour of the clay layer.

Further research will investigate the use of reinforcement in the clay to reduce the severity of the cracks formed when the clay line is subjected to differential settlement and thus ensure that the integrity of the clay structure is able to be maintained.

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