Subsidence effects on clay barriers

H. L. JESSBERGER* and K. J. L. STONE†

Centrifuge model tests have been performed to study the response of clay barriers subjected to differential deformations. The modes of deformation that have been observed are relevant to those that might occur as the result of differential settlements of waste material leading to deformation of cover liners, or from non-uniform soil strength profiles or the propagation of deep-sited subsidence towards the surface, leading to deformations of the base liner. Plane model liners were constructed both from pure kaolin and from a mixture of sand, silica flour and bentonite. The integrity and performance of these model liners were evaluated on a geotechnical centrifuge at 50 gravities. Physical degradation of the model liners was monitored photographically and their performance as effective hydraulic barriers assessed throughout the deformation process. For all the model liners where no overburden was present, tension cracking of the liner surfaces was observed. These tension cracks were very significant in the kaolin models and led to a drastic reduction in liner performance. However, the presence of an overburden suppressed the formation of tension cracks and no significant reduction in the kaolin liner efficiency was observed. The model liners fabricated from the sand, silica flour and bentonite mixture proved to be highly resistant to deformation with little evidence of tension cracking and no significant reduction in performance.

KEYWORDS: centrifuge modelling; deformation; settlement; clays; failure; seepage.

INTRODUCTION

Solid waste disposal in shallow landfill depos-itories has been extensively employed for the permanent disposal of both municipal and industrial wastes. However, such practice has generated much concern over the possibility of environmental contamination resulting from the per-

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Fig. 1. (a) Landfill facility showing (b) mode of liner deformation

of a permanent cover once filling is complete and an acceptable degree of waste stabilization has occurred. Both the base and cover liner systems are commonly fabricated from compacted clay—usually a few per cent wet of the optimum Proctor compaction.

However, such compacted clay liners may fail to perform satisfactorily for several reasons. For example, cover liners are susceptible to climatic effects such as desiccation cracking (Kleppe & Olson, 1985), and frost action (Andersland & Al-Moussawi, 1987), as well as deformations of the liner itself (Sterling & Ronayne, 1982) caused by differential settlements of the contained wastes (Fig. 1(b)).

Similarly, base liners may suffer from chemical attack by the contaminated leachate, as well as differential liner settlements resulting from non-uniform soil strengths below the landfill (Jessberger & Thiel, 1990), or from near-surface ground movements associated with deep-sited subsidence.

The tests reported in this Paper are concerned with the effect of differential deformations on the performance and integrity of clay liners. Previous studies (Stone & Wood, 1988) where part of an underlying basement has been displaced to introduce a discontinuity of slope, but not of displacement, have shown that such continuous boundary deformations can lead to the formation of discontinuities or ruptures in the overlying soil. It is of interest, therefore, to study the response of clay liners subjected to such boundary deformations, and to investigate the parameters which influence the stress-dependent liner response. In particular the behaviour of pure clay and sand–silica flour–bentonite liners (hereafter referred to as the fine/coarse mixture) is investigated and their performance as effective hydraulic barriers is assessed throughout the deformation process.

CENTRIFUGE MODEL TESTS

Centrifuge model testing

It is well known that the behaviour of most soils is very dependent on stress level. In conventional small-scale model tests, performed within the earth's gravitational field, it is not always possible to maintain similarity with prototype situations and to ensure that stress levels in areas of interest reach prototype values. A geotechnical centrifuge can subject small models to centripetal accelerations which are many times the earth's gravitational acceleration. By selecting a suitable acceleration level the unit weight of the soil being tested can be increased by the same proportion by which the model dimensions have been reduced, and thus stresses at corresponding points in the model and prototype will be the same.

The centrifuge model tests reported here were performed on the Bochum 10 m balanced beam centrifuge at an enhanced acceleration level of 50 gravities. Details of the Bochum geotechnical centrifuge are given by Jessberger & Guttler, 1988.

Scaling relationships

Centrifuge scaling relationships have been extensively described elsewhere (e.g. Arulanandan et al., 1988). However, if we consider a model where the prototype dimensions have been reduced \( n \) times such that \( d_p/d_m = n \), where \( d_p \) and \( d_m \) are prototype and model dimensions respectively, and if \( n \) is chosen as the gravity scaling factor then Table 1 illustrates the basic scaling relationships associated with centrifuge modelling.

If the same material is used in both the model and prototype then the similarity of stress levels at corresponding points in the model and prototype will result in a model response directly analogous to that of the prototype. Furthermore, the prototype stress gradient present in the model will ensure similarity of the primary permeability distribution.

Table 1. Centrifuge scaling relationships

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scaling relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity: m/s²</td>
<td>( n )</td>
</tr>
<tr>
<td>Length: m</td>
<td>( 1/n )</td>
</tr>
<tr>
<td>Stress: Pa</td>
<td>1</td>
</tr>
<tr>
<td>Strain: %</td>
<td>1</td>
</tr>
<tr>
<td>Force: N</td>
<td>( 1/n^{2} )</td>
</tr>
<tr>
<td>Time:* s</td>
<td>( 1/n^{2} )</td>
</tr>
</tbody>
</table>

* Applies to laminar flow processes such as consolidation.
Centrifuge model package

The centrifuge model tests were performed in a rectangular strong box of internal dimensions 395 mm wide × 658 mm long × 395 mm high. The front of the strong box is formed by a 70 mm thick perspex window through which deformations of the model can be photographically observed while the model is 'in flight' on the centrifuge.

The model test package is shown schematically in Fig. 2. In order to generate a displacement profile at the base of the model liner a rectangular piston is located centrally in the floor of the strong box. This piston extends the full width of the strong box and has a maximum travel of 25 mm. A false base containing a pair of 95 mm hinged flaps is located across the strong box, and is so arranged that when the piston is lowered the flaps rotate and induce a discontinuity of slope at the base of the overlying soil, as represented by the dashed line in Fig. 2. Linear variable displacement transducers (LVDTs) are used to monitor water levels and linear deformations.

To minimize the possibility of leakage between the liner and the sides of the strong box the overlying water is contained within a shallow trench (model landfill) as illustrated in Fig. 3(a). The depth of surface water present is monitored by an LVDT and float and can be increased by releasing water from vessel A. The water table below the liner is maintained at the pre-set level of standpipe B. The overflow from standpipe B is collected into the cylindrical vessel D. Consequently, by monitoring the rise of the water level in D, the rate of water flow through the liner can be deduced, and hence the average permeability of the liner can be estimated.

While the basic principle of the model is fairly self-evident there are several aspects which

![Fig. 2. Centrifuge model test package](image_url)
require further explanation. These aspects arise from the fact that when the model is accelerated on the centrifuge, the water saturating the sand immediately below the liner is centrifuged down to the level of the water table below the liner maintained by standpipe B. It is possible that during this process a partial vacuum could be created in the voids of the sand directly below the liner. Furthermore, as the liner itself settles, the volume of air trapped between the liner and the lower water table will reduce. This may lead to pressure changes in the sand which may introduce some degree of uncertainty as to the value of the hydraulic gradient across the liner. To avoid this potential problem the sand directly below the liner is vented to 1 atmosphere.

A second consideration is to ensure that the liner itself will not settle into the lower water table and displace water from the model and into the collection vessel D. Thus the level of the lower water table (standpipe B) is set at 27 mm below the base of the liner.

MODEL PREPARATION PROCEDURE

Two different liner materials were chosen. The first was a commercially available kaolin clay (2096c kaolin) supplied by Erbslöeh & Co., F.R. Germany. This clay has a liquid limit of 44.4% and a plastic limit of 28.1%. There is much debate as to the optimum design water content that should be used for compacted clay liners, but for the purposes of this experimental study a moisture content corresponding to 95% saturated Proctor density was adopted. The second liner material was a sand/silica flour/bentonite mixture of the proportions given in Table 2.

This model liner material was chosen to represent the prototype mixture shown by curve A in Fig. 4(a). As can be seen in this figure the prototype mixture contains a large gravel fraction. For the model tests this gravel fraction was scaled down and replaced by a coarse sand to produce the grading curve B in Fig. 4(a).

Particle size effects in model testing, where the particle size of the prototype has not been

![Grading curves for prototype and model fine/coarse mixtures, and Proctor compaction for 2096c kaolin](fig4.png)
reduced to the model scale, has been the source of much debate in the literature (e.g. Ovesen, 1979; Kimura et al., 1985). In general it has been assumed that, provided the ratio of a critical model dimension (i.e. a footing diameter) to the particle size is sufficiently large, no significant size effects will be apparent. If, for the tests reported here, the liner thickness is considered to be a critical model dimension then it is clearly necessary to scale the gravel fraction of the prototype fine/coarse mixture. In so doing the ratio of coarse particle size to liner thickness in both the model and prototype is preserved.

Model preparation

After all the internal components have been fitted into the strong box a 30mm layer of coarse sand overlain by a further 45mm of fine sand is rained into the strong box. A layer of filter paper is placed just below the final sand surface to prevent fine particles of the liner material from being washed out. A row of discrete markers is placed against the perspex window on the sand surface for subsequent digitization from 'in flight' photographs. The sand is then saturated by the upward percolation of water introduced via a network of drainage holes at the base of the strong box. After greasing the internal sides of the strong box the model is ready for liner fabrication.

Kaolin liner preparation

Kaolin slurry was placed by hand (to avoid air entrapment) to a pre-determined depth over the saturated sand. A consolidation unit was then attached to the strong box and the slurry was one-dimensionally consolidated to a final vertical effective stress of 630 kPa. This final effective stress level results in the liner attaining a moisture content of 32.5% which is consistent with the moisture content associated with a 95% (saturated) Proctor compaction density (see Fig. 4(b)). After removing the consolidation unit a shallow landfill was excavated in the consolidated liner (see Fig. 3(a)).

Fine/coarse mixture liner preparation

For the tests reported here two methods were used to prepare the fine/coarse liners. For test KBD1 (no overburden) the material was mixed to a moisture content of 35% and placed by hand to the required depth. A vertical pressure of 100 kN/m² was then applied for three days. This method of liner preparation was intended to produce a fully saturated sample prior to mounting on the centrifuge in a relatively short time. For tests KBD2 (no overburden) and KBD3 (with overburden) the fine/coarse mixture was placed dry and vibro-compacted in approximately 10mm thick layers before saturation by upward percolation. A plastic former was used to shape the model landfill during the placement of the material and a small pressure (0.05 kPa) was applied to prevent uplift of the liner during saturation. This method of liner preparation is more representative of the prototype placement method but it has the disadvantage of requiring a long saturation time prior to testing. However, comparison between the liner responses of test KBD1 and KBD2, where similar liners were constructed by the two methods outlined above, showed no detectable differences in liner response. Consequently the results reported here will focus on tests KBD1 and KBD3 which can be considered as typical for geometrically similar liners irrespective of their preparation procedure.

CENTRIFUGE MODEL TEST RESULTS

The corresponding model and prototype boundary conditions for the tests reported here are given in Table 3. The principal objective of the model tests was to investigate the physical response of model liners subjected to various degrees of deformation, as illustrated through the

<table>
<thead>
<tr>
<th>Test</th>
<th>Liner material</th>
<th>Liner thickness D</th>
<th>Depth of overburden B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mod: mm</td>
<td>Pro: m</td>
<td>Mod: mm</td>
</tr>
<tr>
<td>TD8</td>
<td>Kaolin</td>
<td>35</td>
<td>1.75</td>
</tr>
<tr>
<td>TD9</td>
<td>Kaolin</td>
<td>35</td>
<td>1.75</td>
</tr>
<tr>
<td>TD10</td>
<td>Kaolin</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>KBD1</td>
<td>Fine/coarse</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>KBD2</td>
<td>Fine/coarse</td>
<td>45</td>
<td>2.25</td>
</tr>
<tr>
<td>KBD3</td>
<td>Fine/coarse</td>
<td>45</td>
<td>2.25</td>
</tr>
</tbody>
</table>
development of cracks and ruptures. The effect of overburden and choice of liner material on the model response was observed. In addition, the performance of the liners as effective hydraulic barriers was monitored throughout the deformation process. This enabled the effects of losses in liner integrity, such as cracking, to be quantified.

As already mentioned the liner deformations are induced by the vertical translations and rotations of the piston and flap arrangement located at the base of the sand layer. However, these movements cannot easily be related to the actual degree of deformation suffered by the liner. Consequently, the degree of liner deformation is defined as the degree of rotation $\theta$ (see Fig. 1(b)) that has occurred at the base of the liner. This angle is deduced from digitized recordings of the discrete markers placed at the sand/liner interface.

Tension cracking and rupture

Figure 3(b) shows a post-test photograph of the model liner surface of test TD10 after a liner deformation of 8°. Severe tension cracks are clearly evident in the regions of maximum liner deformation. The development of such tension cracks was a typical feature of the pure kaolin clay liner tests where no overburden was present. The degree of liner deformation at the onset of tension cracking was seen to be a function of liner thickness (see Jessberger et al., 1989).

For the tests reported here the onset of tension cracking was observed at 3 to 3.5" for the pure kaolin tests TD8 and TD10. After washing away the sand overburden in test TD9, no tension cracking was evident with a liner deformation of 11°. For the fine/coarse liner with no overburden (test KBD1) slight surface cracking was observed at a liner deformation of 7.5° but no significant cracking developed even after the maximum liner deformation of 16° had been attained. For the case with overburden (KBD3) no surface degradation of the liner was observed after washing away the overlying sand.

After each test the perspex front face of the strong box was removed and the model liner sectioned to examine the depth of tension cracks and the presence of any other internal damage. For tests TD8 and TD10 the tension cracks were seen to extend almost vertically towards the base of the liner (see Fig. 5(a)). Careful sectioning of test TD9 revealed no further evidence of tension cracking; however, a series of multiple shear ruptures in the regions of greatest liner deformation were observed curving out over the break in slope (see Fig. 5(b)). Finally, post-test examination of the deformed fine/coarse liners did not reveal any significant material degradation, and only shallow surface cracking in the regions of greatest liner deformation were visible for tests KBD1 and KBD2.

Assessment of liner performance

The performance of the model liners as effective hydraulic barriers is best illustrated through the rate of leachate (water) flow through the liner. This flow rate is directly observed by the rise of the water level in collection vessel D (see Fig. 2). However, conversion of this flow rate to an average value of liner permeability is complicated by the non-uniform hydraulic gradient present across the model liner. This arises from two conditions. The first condition is unique to centrifuge modelling and is the tendency of water levels in centrifuge models to align along lines of equal radius from the axis of centrifuge rotation. Thus the surface water level within the model landfill will at all times maintain a concave curvature. However, as already mentioned, the water in the sand directly below the base of the liner is centrifuged down to the lower water table (see Fig. 2) which results in the base of the liner becoming a horizontal potential surface for the undeformed liner. Consequently a variation in the hydraulic gradient across the liner will exist due to the curved nature of the free surface water table above the liner. Secondly, the deformations introduced during the test will result in increased hydraulic gradients over areas of liner depression. Fig. 6 illustrates how the hydraulic gradient across the model liner varies as a function of surface water level and liner deformation. In the light of these and other complications discussed later in this Paper, the values of average permeability stated herein should be treated with caution.
SUBSIDENCE EFFECTS ON CLAY BARRIERS

Fig. 6. Variation of hydraulic gradient across model liner

Figure 7(a) shows the settlement record of the centre of the model liner superimposed on the LVDT trace monitoring the water level in the collection vessel D for test TD10. This is a typical test result for a kaolin clay liner with zero overburden and illustrates the following characteristic behaviour. From A to B the centrifuge is accelerated up to speed and the collection vessel D is rapidly filled and discharged as water in the underlying saturated sand is centrifuged down to the pre-set level of the lower water table (see Fig. 2). From B to C there is still a significant flow into vessel D as water continues to be expelled from the sand and from the self-weight consolidation of the clay liner. From C to C' it can be assumed that no more water is being forced out of the sand and that the amount of water originating from the liner itself is minimal. From this flow rate an initial value of average liner permeability was found to be $1.3 \times 10^{-9}$ m/s. From C' to D the flow rate is seen to increase while a deformation to $3^\circ$ is introduced at the base of the liner. This increase in flow rate will again be partly due to dissipation of excess water pressures in the liner itself, and so a realistic calculation for permeability cannot be made during the actual deformation process. However, for the region D

Fig. 7. (a) Selected transducer records (kaolin liner, no overburden) and (b) angle of liner deformation against flow rate through liner for test TD10
to E the value of average permeability was found to be $1.18 \times 10^{-9}$. This value suggests that, within experimental error, no detectable change in liner permeability has occurred with a deformation of 3" present.

Further deformations are introduced (E to F) but again there are no significant increases of flow rate through the liner until a deformation of 6" is obtained at F, at which point a dramatic increase in flow rate into vessel D is observed. The subsequent reduction in flow rate (F to G) before further deformation indicates a self-healing potential of the clay. The behaviour of all the kaolin clay liners without overburden exhibited a similar behaviour to that illustrated by Fig. 7(a).

Figure 7(b) shows a plot of angle of liner deformation against flow rate through the liner as derived from Fig. 7(a). This plot further illustrates the dramatic increase in flow rate through the liner at an angle of base deformation of 6°.

The onset of a sudden increased flow rate through the liners can be considered a serious ‘failure’ of the liner, and corresponds to the development of deep tension cracks and ruptures forming a preferential flow path through the liner in the regions of maximum deformation. For the kaolin liner test performed with an overburden pressure (test TD10), no such liner failure was observed, and it can be concluded that the presence of the shear ruptures did not significantly affect the liner’s performance.

Comparison of kaolin and fine/coarse mixture liner performance

The fine/coarse liner model (test KBD1) was made to the same initial boundary conditions as test TD10 and subjected to a similar deformation history to enable a direct comparison between liner performances to be made. Figure 8 shows a plot of liner settlement and leachate collection level for the full duration of test KBD1. Comparison of this plot with the corresponding record for test TD10 (Fig. 7(a)) illustrates some fundamental differences.

Firstly, the initial flow rate reduces to virtually zero (region A to B) indicating an extremely low permeability of the model liner. As observed for the kaolin test, the flow rate increases during deformation but approaches zero again soon after stopping the deformation (region B to C). This behaviour is repeated until 9-5° of liner deformation is achieved (at D), at which point a permanent increase of flow rate is observed from which an average permeability of $1.89 \times 10^{-10}$ m/s is deduced. On further deformation to 11-5° the flow rate into vessel D increases slightly but then remains constant for the remainder of the deformation process. The final average permeability for the liner of the end of the test, with a deformation of 16°, was estimated as $2.915 \times 10^{-10}$ m/s. As for the kaolin liner tests, these increases in flow rate at high degrees of liner deformation are likely to be the result of local changes in permeability in regions of severe liner distortion. It should be noted that at such large deformations the assumption of a smooth profile of differential settlements at the base of the liner is no longer applicable, since deformations within the underlying sand will have localized into thin bands of intensely shearing material. The intersection of these shear planes with the base of the liner will generate local discontinuities of both

![Fig. 8. Selected transducer records for test KBD1 (fine/coarse mixture liner, no overburden)
slope and displacement. Consequently the values of average permeability are somewhat misleading. It is not possible at this stage to make any statements about local permeability changes within the model liners, but clearly the severe liner ‘failure’ observed for the kaolin test TD10 is not evident with the fine/coarse liners. The response of the fine/coarse liner test KBD3 (with overburden) was very similar to that described above for test KBD1 (no overburden) except that no detectable increases in flow rate through the liner were observed for the duration of the test, i.e. for the full induced liner deformation.

DISCUSSION

The tests reported in this Paper were performed to investigate the effect of overburden and choice of liner material on the response of a model liner to imposed deformations. The kaolin model liner responses were significantly different depending on whether or not an overburden was present. In the presence of overburden no tension cracking was evident and the formation of multiple shear surfaces was observed, which is in contrast to the case with no overburden where significant cracking was observed. The suppression of tension cracking can be explained, at least in part, by a simple elastic interpretation of the material response. The increased initial lateral stresses generated within the liner as a result of the overburden (see Fig. 9) allow greater distortion of the liner to occur before tensile stresses necessary for cracking are generated. However, before such stress levels are reached, localization of deformation occurs with the formation of multiple shear ruptures in regions of greatest liner deformation. Consequently, tensile stresses necessary for cracking do not arise and no tension cracking is observed once rupturing has occurred.

It is not possible at this stage to make any statements as to when shear rupture occurs and what combination of overburden and liner thickness is necessary to prevent tension cracking. The presence of shear ruptures did not affect the performance of the kaolin model liner as an effective hydraulic barrier. However, there is some evidence that in the presence of large hydraulic gradients this is not necessarily the case, and such ruptures could provide preferential flow paths (Gronow, 1988) reducing liner effectiveness.

Where no overburden was present the growth of tension cracks in regions of large deformation resulted in the failure of the pure kaolin model liners to function as effective hydraulic barriers. However, in liners of greater thickness the larger lateral stresses present in the lower depths of the liner may also result in the onset of shear rupture rather than continued tension cracking, as argued above for the case of an overburden. In such instances a liner failure would arise from the creation of preferential flow paths consisting of a combination of shear rupture and tension cracking. This was thought to be the case in test TD8 (see Fig. 5(a) for interpretation).

Comparison of the fine/coarse and pure kaolin model liners illustrates a much greater capacity of the fine/coarse model liner material to function effectively when subjected to even large deformations. The reasons for this response are not entirely clear, but the following interpretation is suggested. Firstly, the absence of significant tension cracking suggests that the material possesses a very small apparent cohesive strength and hence large unsupported tension cracks cannot appear. That is to say the response to deformation of the material is as might be expected for a sand. Secondly, the very low permeability of the material, which is derived from the nature and size distribution of the fine fraction, is maintained under imposed deformation by the ability of this fine fraction, which would behave like a slurry of near-zero effective strength, to ‘flow’ within the sand matrix. Hence the material would exhibit an extremely quick and efficient self-healing property. While this interpretation offers one possible explanation for the response of the fine/coarse material it is, nevertheless, purely conjectural.

Observations from simple shear tests—a mechanism not far removed from that experienced by the model liners—suggest that the extent to which internal ruptures extend through a clay sample is dependent on the plasticity of the

![Fig. 9. Influence of overburden on lateral stress level](Image)
clay (see for example, Airey et al., 1985). Recent studies by Henne (1989) on the bending response of compacted clay specimens, has shown that the deformations necessary to induce tensile cracking increase with the plasticity of the clay. Consequently the tendency of the fine/coarse mixture not to fail by tensile cracking could be related to the fact that the material possesses high plasticity. However, it is not possible within the scope of this initial study to relate the deformation response of the model liners to their laboratory stress–strain response, and further studies of the material properties are required before any definitive statements can be made.

CONCLUSIONS

The ability of the centrifuge to induce prototype stress levels within a small-scale model allows the stress-dependent response of the model to be interpreted directly for the corresponding prototype situation. Thus, from the model tests presented in this Paper, where model liners have been subjected to deformations of a similar nature to those that might occur in the field, the following conclusions can be drawn.

(a) Tension cracking and rupture are likely responses for pure compacted clay liners. The dominant mode of liner response will be dependent on the lateral stress level. For example, small lateral stresses will favour the development of tension cracking whereas larger lateral stresses will promote localization of deformation into shear ruptures.

(b) The development of severe tension cracks can lead to failure of the liner to function as an effective hydraulic barrier.

(c) The presence of ruptures alone is perhaps unlikely to affect the satisfactory performance of the liner in a prototype situation.

(d) Liners manufactured from fine/coarse type mixtures may provide hydraulic barriers virtually unaffected by likely prototype deformations.

REFERENCES


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