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Bending experimentation of a composite clay-geosynthetic liner

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ABSTRACT: To further knowledge of the behaviour under bending of cover layers subject to differential settlement of waste in landfill centres, large scale experiments have been performed on instrumented earthworks. Layers of clay of different thicknesses, reinforced at the base or not by a geosynthetic sheet, were tested for bending under their own weight and then under load. Displacements and strains of the clay layer were measured at each step of the experiment. The Distinct Element Method were used to provide comparative information and better understanding of the mechanisms involved.

1 INTRODUCTION

Because of the heterogeneity and decomposition of waste in waste landfill centres, the surface cover, notably consisting of a thick clay layer, in accordance with various environmental regulations, is often submitted under great displacement due to differential settling or sudden subsidence which can cause the material to crack, severely compromising its capping role. Another possible cause of cracking clay is desiccation but that is not envisaged in this document.

To further knowledge of the behaviour of clay layers under bending, a vast research programme has been instigated, including laboratory tests, large scale experiments and numerical modelling.

Laboratory tests (tensile test, simple compression, bending, splitting and punching) were performed at Lirigm, Grenoble (N. Madjoudj, 2001) to characterize the behaviour of clay cover layers under bending-tensile.

Large scale experiments (S. Thomas, 2000) were performed in June 1999 in association with the French environmental agency (ADEME) and FAIRTEC on two instrumented earthworks. The aim of these tests was to monitor the bending behaviour of waste landfill cover in the short and long term, under its own weight then under gradual load, and to verify that after deformation, the clay cover still fulfils its functions.

The modelling took place in Lirigm, Grenoble, using a Distinct Element Method. This type of approach provides models of behaviour for fractured environments and is suitable for the problem in question (displaying networks of cracks).

2 LARGE SCALE EXPERIMENTS

2.1 *Description of two earthworks*

The experiments were performed on the CERED site at Vernon in the Eure department, on clay material with a large proportion of coarse soil (material conventionally used in France for waste landfill centres). The first layer of unreinforced clay, was tested for bending over a length L of 2 metres, at a thickness H of 1 metre, while the second, reinforced at the base by a geosynthetic sheet (Bidim Rock Pec 2000), was tested at a thickness H reduced to 0.6 m (fig.1). The tensile stiffness of the geosynthetic sheet (overall length of 8 m) is J=1818 kN/m. The anchorage of the sheet (free ends) is obtained by friction (no sliding occurred). The earthworks are flat and have a width d of 2 m.

The clay was implemented in successive sub-layers 0.3 m to 0.4 m thick, and compacted to a water content w of 28 %. The dry unit weight of the material γ_d was 14.5 kN/m^3 and the Proctor optimum characteristics are: w_{opt} = 22.6 % and γ_{opt} = 15.6 kN/m^3. The Atterberg Limits of the material are W_L = 72 % and W_P = 24 %. At the base of each earthwork, a cavity of (2 m x 2 m) filled with expanded clay beads, simulated subsidence of the waste on emptying and put the flexing clay layer under bending.

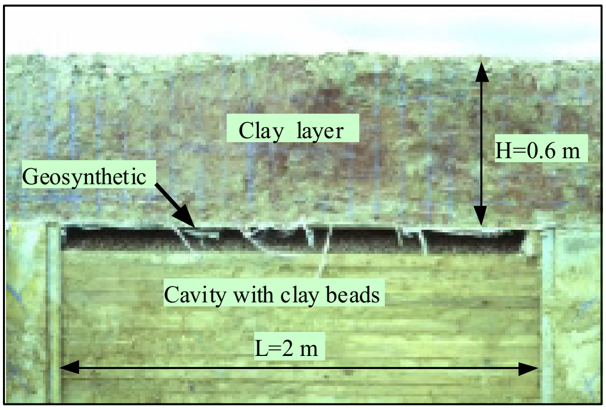

Figure 1. Front view of the reinforced earthwork.

2.2 *Instrumentation*

The instrumentation used was intended to monitor displacement, strain and cracking of the clay layer.

The front of the earthwork was divided into a grid (0.1 m x 0.1 m) and photographs were taken at regular intervals during the experiment. Stereophotogrammetric analysis was used to produce a map of strain in the clay layer and cracking.

Vertical displacement was also measured on the front of both earthworks at different steps of the experiment (short and long term).

To determine vertical deflection within the clay layer, horizontal inclinometers were installed at two levels in the thickness of the clay layers, at the base and at the interface between the first 2 compaction sub-layers, i.e. at 0.4 m from the lower limit in the unreinforced layer and at 0.3 m for the reinforced earthwork (fig.2).

Inclinometers are hollow square tubes (40 mm x 40 mm) made of aluminium, with certain sections (three in the central part) partly sawn through to facilitate bending when deformation was applied to the clay. However, this system proved to disturb the experiment. The sections on the right of the cavity were not sawn and this led to non-negligible amounts of strain being taken up by the inclinometers bending at that level. On installation, the inclinometers were set on a bed of fine sand to protect them during compaction. These thin strips of sand which sometimes extend horizontally for up to 0.3 m on either side of the inclinometers, affected a considerable area of the adhesive earthwork between the sub-layers of clay.

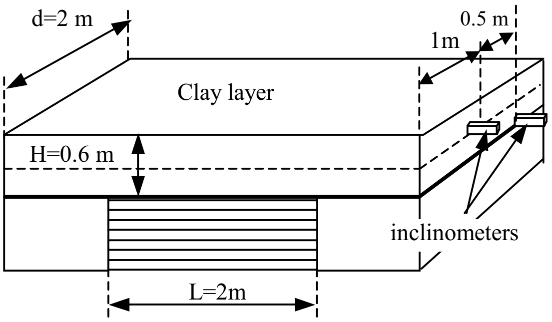

Figure 2. Position of inclinometers for the reinforced earthwork.

2.3 *Test procedure*

After viewing the behaviour of the clay layer under bending under its own weight (removing clay beads), the earthworks were gradually loaded until the clay layer partly or totally ruptured.

3 RESULTS OF EXPERIMENTS

3.1 *Barrier of reinforced clay*

Observation of the initial appearance of the earthwork before emptying revealed a horizontal crack midway up the front surface of the clay layer, probably due to the presence of the sand added when installing the inclinometers.

Once emptied, there was distinct loosening between the lower and upper sub-layers of clay, revealing cracks inclined towards the edges of the cavity (fig.3). The lower sub-layer behaved independently like a 0.3 m layer subject to bending under its own weight. The geotextile followed the deformation of the lower sub-layer and was not under much stress: the maximum vertical displacement of the lower sub-clay layer being still small (f = 10 mm). The upper sub-layer did not deform very much under its own weight.

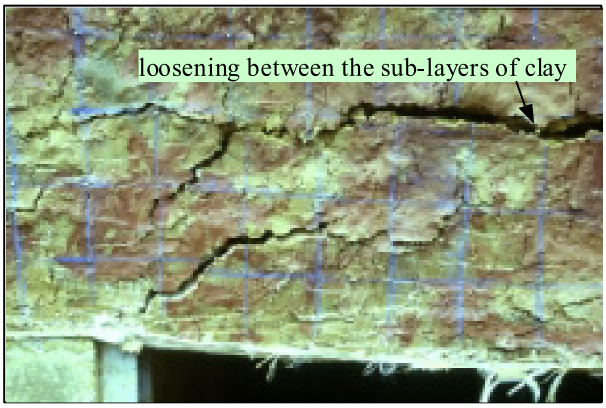

Figure 3. Cracking of the clay layer on the right of the cavity.

The earthwork was put under progressive stress on the surface with a distributed load q consisting of concrete blocks (fig.4). The upper sub-layer of the earthwork was gradually put under strain until it was again in contact with the lower sub-layer so that the horizontal crack was closed and the geosynthetic liner put under stress by the membrane effect. Major vertical displacement (f = 0.14 m) took place at the bottom of the clay layer at the end of loading (fig.5).

To study the earthwork's long term behaviour, it was put under stress under a constant load (q=3.5 kN/m²) for several months. An increase in vertical movement of the clay and geosynthetic liner was observed, following the gradual diffusion of stress through the structure.

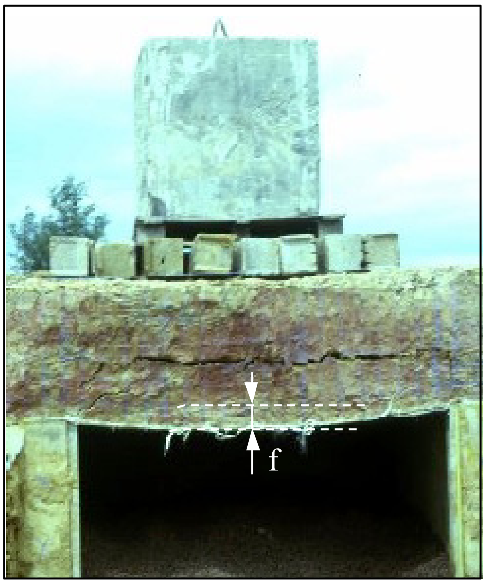

Figure 4. Loading the reinforced earthwork with concrete blocks.

The analysis of photographs taken during the test allowed us to trace the curve (fig.5) of vertical displacement f at the base of the lower clay sub-layer according to the total vertical load applied Q (own weight of the clay layer under consideration + overload q).

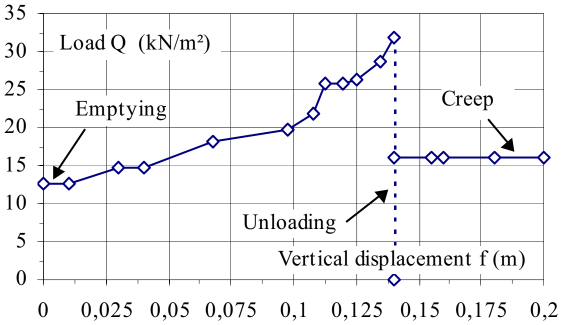

Figure 5. Curve of vertical displacement / loading for the lower sub-layer in the reinforced earthwork.

3.2 *Barrier of unreinforced clay*

The initial observations made on the front of the unreinforced earthwork revealed a network of cracks similar to that observed in the reinforced earthwork. The horizontal crack due to interlayer detachment because of the presence of sand split the earthwork into two sub-layers about 0.4 and 0.75 m thick.

While emptying the expanded clay beads we could observe the gradual subsidence of blocks of the lower sub-layer by 0.4 m (fig.6). The upper sub-layer did not move. After cutting the lower inclinometric tube and completely emptying the cavity, the lower sub-layer was completely destroyed. The barrier's behaviour during the rest of the experiment will be assumed to be the same as that of a clay layer about 0.75 m thick.

Figure 6. Collapse of the lower sub-layer of the unreinforced earthwork during emptying.

The upper clay layer was loaded, unloaded rapidly and then put under stress once more. During these loading / unloading phases, we observed the gradual appearance of a network of cracks which, under heavy load, caused partial subsidence of the clay layer, remaining in the form of an arch. This arch spread the load onto the embankment around the cavity. Although the upper inclinometer was sawn in its central part during loading, its ends were held in the healthy clay layer and still helped to support the arch. At this stage, considering the major strain obtained, the clay layer was considered to have been destroyed.

The curve of displacement f at the base of the upper sub-clay layer according to the total vertical stress applied Q (own weight of the clay layer under consideration + overload q) is shown in figure 7. Note that during the unloading phase the behaviour of the clay layer was not reversible. The slopes of the force / displacement curve before and after unloading are parallel. The difference observed is due to an additional sag of about 20 mm.

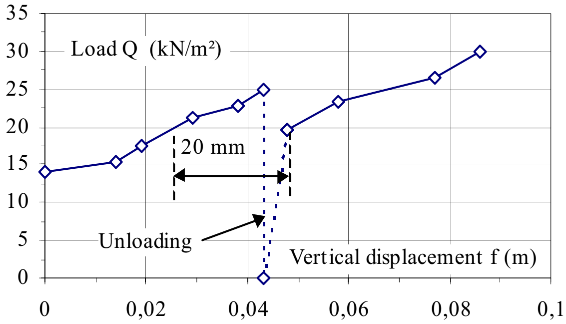

Figure 7. Curve of vertical displacement / loading of the upper sub-layer in the unreinforced earthwork.

4 MODELLING

4.1 *The Distinct Element Method*

The approach taken to model the behaviour of layers of clay on bending is based on the Distinct Element Method. This method was originally developed by Cundall and Strack (1979), and is used to discretize a homogeneous medium by assembling independent elements of various sizes which interact at their points of contact. This method is used in geomechanics, notably for granular or fractured media.

The software used for our study (Itasca PFC^{2D}) can process two-dimensional problems. The basic particles used are circular. They can be combined to form rigid assemblies of various shapes.

The behaviour of particles is governed by elastoplastic laws of contact: normal and tangential rigidity for elastic behaviour, criteria for tensile and shear failure for plastic behaviour. These local laws gave all the grains a Mohr-Coulomb type global behaviour. The correspondence of micromechanical parameters (contact parameters) and global behavioural parameters (geomechanical parameters) requires calibration between experimental and theoretical models in standard tests.

Numerical simulations were produced with the aim of improving knowledge of the behaviour of layers of clay under bending. The comparisons made between modelling and experimentation remain indicative, considering the high level of uncertainty linked to the presence of inclinometers and layers of sand, the influence of which will be taken into account in one of the two models.

4.2 *Modelling the experiment on a reinforced earthwork*

The hypotheses defined for modelling the behaviour of the reinforced earthwork were estimated at best from the experimental data. The membrane behaviour of the geotextile (deformation of the geotextile following the action of loading perpendicular to its plane) and of clay under tensile-compression were correctly modelled with calibration, using characterization tests performed in the laboratory (tensile and compression). The modelling parameters are: tensile stiffness J of 1818 kN/m for the geosynthetic sheet, cohesion C of 17 kPa, an angle of internal friction ϕ of 40° and modulus of elasticity of 12 MPa for clay.

It is assumed that the layers of sand (non-cohesive material) are present throughout the width of the whole earthwork at the level of the geosynthetic and at mid-height in the clay layer.

The behaviour of the inclinometers on the right of the cavity was assimilated to that of a built-in beam, with bending stress due to a uniform load spread over a length of 0.5 m (inclinometer tube sawn in certain sections). The maximum distributed load necessary for an inclinometer tube to bend was estimated on the basis of its mechanical and geometric characteristics at 5.54 kN/m. Equivalent distributed loads (the action of which will be subtracted from the weight of the clay layer itself) was applied to the model. More sophisticated modelling, taking into consideration the three-dimensional aspect of the problem, seemed pointless in view of the negligible advantage of using inclinometers in an actual case.

A rigid plane was modelled on the basis of the clay layer. The removal of this rigid wall simulated emptying the cavity.

Each phase of the experiment was modelled: strain under own weight and gradual loading to Q = 32 kN/m². The vertical surface loads were distributed over the clay layer using eight juxtaposed rigid plates.

The results of simulation (movement of particles of the clay layer) are given for different steps of loading in figures 8 and 9. It was noted that, on emptying and under a light load (fig.8), the upper and lower sub-layers of clay were loosened and there were signs of cracking on the right side of the cavity.

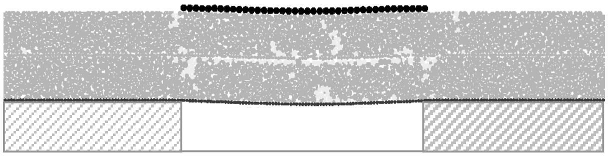

Figure 8. Displacement of the clay layer (q = 2 kN/m²).

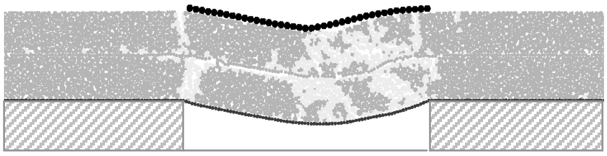

Figure 9. Displacement of the clay layer (q = 6.5 kN/m²).

Under a heavy load (fig.9) the two sub-layers of clay on the geosynthetic liner were seen to subside along a network of cracks similar to that observed in the experiment itself. The geosynthetic sheet in the position of a membrane, absorbed all the loads applied at this stage of modelling.

The curve of central vertical displacement f of the clay layer according to the total load applied Q is compared to the experimental curve in figure 10. The theoretical curve quickly reveals a brittle tensile strength which was not observed experimentally (probable action of the inclinometers). In the long term, vertical movement of the clay layer is fairly close to that given by modelling.

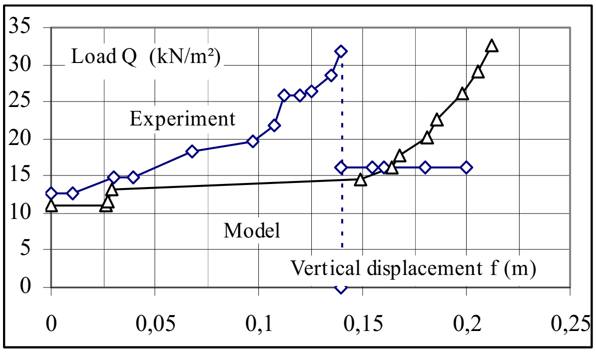

Figure 10. Comparison of experimental and numerical curves.

4.3 *Modelling the behaviour of bending of a clay layer of 0.6 m*

The purpose of the modelling detailed in this paragraph, is to learn more about the behaviour of layers of clay on bending under normal conditions of use (no inclinometer and no layer of sand). The method of calculation and parameters used are identical to those presented previously.

Simulations were performed on layers of clay 0.3, 0.4 and 0.6 m thick, reinforced at the base by a geosynthetic liner. The results obtained show that only the 0.6 m thick layer is stable under its own weight. These results must be compared with the experimental results which show that the lower sub-clay layer, which is 0.4 m thick, in the unreinforced earthwork breaks on emptying, whereas the thicker upper sub-layer is stable.

The results of simulations made on the 0.6 m clay layer are presented for the different steps of loading shown in figures 11, 12 and 13. Figure 11 gives the distribution of intergranular contact stress (intensity of compression stresses between each particle) obtained on emptying (distribution in the form of an arch). Figures 12 to 13 show zones of cracking and displacement of the clay layer for different values of q.

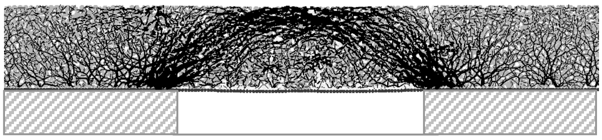

Figure 11. Distribution of intergranular contact stresses on emptying.

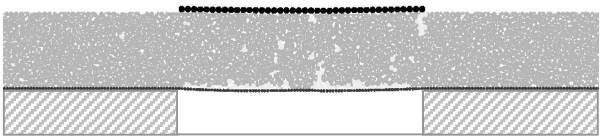

Figure 12. Displacement of the clay layer (q = 5 kN/m²).

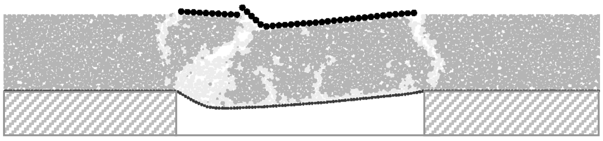

Figure 13. Displacement of the clay layer (q = 6.5 kN/m²).

In figure 13, it is noted that rupture of the clay layer is brittle and follows a block mechanism. The location of the cracks and the mode of rupture depend on the initial distribution of particles. Considering the random nature of this distribution, the example shown displays localization of strain on the left of the model.

The maximum displacement curve f at the base of the clay layer as a function of the total vertical force applied Q, is compared in figure 14 with that obtained by the previous modelling (H=2 x 0.3 m). The maximum sag of the geosynthetic, according to the model, is centered on the sheet (fig.9), or moved towards the left (fig.10), explaining the differences in behaviour noted in figure 14 after the clay layer has ruptured.

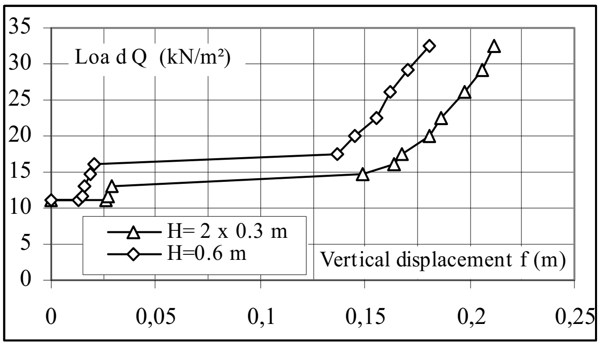

Figure 14. Comparison of displacement / loading curves.

5 CONCLUSION

The work initiated during this study has led to a first analysis of the behaviour of clay cover under bending by the Distinct Element Method. In spite of the difficulties encountered during the experimental phase, the experiments performed provide an interesting basis for comparison with modelling.

The results obtained by the Distinct Element Method are qualitatively and quantitatively interesting (correct reproduction of modes of rupture and fractured zone).

The experiments showed the importance of geosynthetic reinforcement on limiting displacement when the clay layer is ruptured.

Further experiments must be performed to confirm the first results obtained. Hydraulic coupling to determine the influence of the network of cracks on the permeability of the clay layer appears to be particularly interesting.

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