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ABSTRACT

The paper describes the mechanical behaviour of double porosity clay fills. A trial embankment had been constructed on a 20-30 year-old landfill and monitored for 3 years. The embankment was instrumented by hydrostatic levelling profiles, surveying reference points, pore pressure gauges, inclinometers and depth reference points. Centrifuge modelling of the embankment behaviour on the consolidated landfill was carried out in the geotechnical centrifuge at ETH Zürich in Switzerland. The models were instrumented similarly to the real embankment with pore pressure transducers and a newly developed tool called "system of straws" for measurement of deformation at different depths. Surface deformations were measured by laser scanning. The results of centrifuge modelling are compared with in-situ data. The degradation of the double porosity structure in the vertical profile of the landfill, and its influence on the permeability of the soil is discussed.

INTRODUCTION

In Northern Bohemia (north-western part of the Czech Republic), open-cast mining of brown coal has been taking place for more than 60 years. The coal seam is up to 30m thick and it is located at a depth of about 150 metres. The overburden consists of Tertiary clay and claystone of high plasticity. The porosity of intact clay is 40%, liquid limit is 72% and plasticity index is 45%. The mineralogical composition of the clay, determined by X-Ray diffraction, is 36% kaolinite, 25% smectite, 11% illite and 21% quartz. The clay overburden is excavated in irregularly shaped lumps with diameter varying from a few millimetres up to 50 cm and placed in large spoil heaps outside the mines. These clayey fills are up to 100 metres deep. Mine pits are also backfilled with excavated soil after their exploitation. The thickness of the internal fills can reach 200 m. The total area of landfills is more than 100 km^2.

The defining feature of the landfills is their double porosity structure. Two distinct porosities can be identified: that of the intact clay lumps (intragranular porosity) and that of the voids between the clay lumps (intergranular porosity). The total porosity of the fresh fill can reach 70%. Soon after filling, the soil can be described as a granular material (Fig. 1). During time, the structure of the landfills changes and they behave more like a uniform fine grained material. The process of degradation of the double porosity structure was studied by Feda (1998), who described four transition mechanisms typical for self-weight consolidation of landfills: "*crushing of fragments*" takes place more often with wet clay lumps as they are weaker than dry lumps; "*squashing of lumps*" is characteristic of wet lumps, which are compressed and deformed in a ductile manner; "*fragment rearrangement*" comprises sliding and rotation of the lumps which leads to overall densification of the soil; "*contact bonding*" is typical for wet clay lumps, which stick one to another. The main result of the first three mechanisms is a reduction of interlump voids. The rate of structural degradation depends mostly on the vertical stress and degree of saturation of the lumps. Even 20-30 years after landfill construction, the soil is not fully homogeneous and the double porosity structure remains in the soil, especially in the upper parts of the landfills.

Double porosity soils are also intensively studied outside the Czech Republic. A similar problem with large spoil heaps resulting from open pit mining can be found in central Germany. In Sweden, consolidation of an instrumented embankment from clay lumps dredged from the sea in Halmstad harbour was described by Hartlen and Ingers (1981). An extensive study was carried out in Singapore, where dredged clay lumps are used for land reclamation. Research

Fig. 1. Fresh landfill.

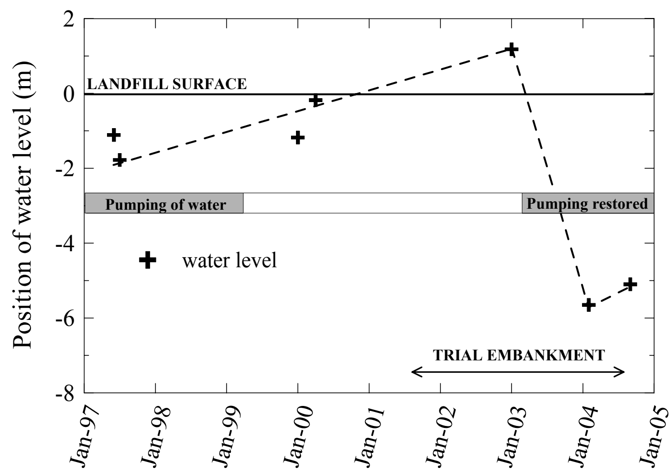

Fig. 2. Variation of ground water level during the monitoring of embankments.

here includes the site investigation of an artificial island constructed of clay lumps (Karthikeyan et al., 2004), modelling soil consolidation using the dual-porosity model (Yang et al., 2002) and FE methods for modelling the non-linear behaviour (Yang and Tan, 2005). Laboratory testing and centrifuge modelling of the consolidation of lumpy clay was described by Robinson et al. (2005), Manivannan et al. (1998) and Leung et al. (2001). However, the behaviour of the lumpy fill in the each site was influenced by the soil properties, shape of the lumps, lump size distribution, groundwater conditions and stress history, so the results of the previous research cannot be directly applied to the specific conditions of the landfills in the Czech Republic.

TRIAL EMBANKMENT

A new motorway between Prague (Czech Republic) and Dresden (Germany) crosses an area influenced by the open pit mining. Before construction of the motorway, a trial embankment was built at a site on its route where a partly backfilled mine pit had been used as a fly-ash lagoon. The thickness of the clayey fill under the embankment was 30 m. The subsoil under the clayfill is Tertiary overconsolidated clays and claystones (Škopek and Boháč, 2004). The age of the landfill was about 20-30 years at the time of embankment construction. The embankment had been instrumented and monitored for 3 years.

The embankment was constructed in August 2001. Pumping of the water in the fly ash lagoon was interrupted in the period 1999-2003, so the water table rose above the surface during the embankment construction (Fig. 2). In 2003 pumping was restarted and the water level decreased to almost 6 m below the surface. The embankment was 8m high with crest dimensions of 20 by 35 m. It was instrumented with 18 surveying reference points on the landfill surface and at the top of the embankment, hydrostatic levelling profiles at the base of the embankment and depth reference points, inclinometers and pore pressure gauges in the embankment subsoil. Flexible plastic tubes for hydrostatic levelling were installed in two profiles perpendicular to the axis of the embankment. The position of the depth reference points was measured in two boreholes instrumented by plastic tubes with 5 (6) outside-mounted free moving magnetic rings. The deepest reference point was installed 27.6 m below the landfill surface. Gauges for the measurement of pore water pressure were installed at three different depths (3, 6 and 10 m below the original surface). A detailed description of the monitoring and discussion of the results can be found in Škopek (2001) and Škopek and Boháč (2004).

Results of monitoring

Figure 3 shows the results from hydrostatic levelling profile 1. The rapid settlement immediately after embankment construction was followed by an additional small deformation. No measurements were carried out from 2002 until July 2004 due to the rise of the water level above the soil surface. The settlement in this period was influenced partly by restarting pumping (Fig. 2) and partly by creep. Large variations in maximum settlement between hydrostatic levelling profiles were measured (differential settlement reached about 10 cm). The rate of settlement in the central axis of the embankment is plotted in Fig. 4. The large initial settlement occurred over a relatively long time interval due to the gradual construction of the embankment, which was completed in 34 days.

A similar trend can be observed in the measurement of the depth reference points (Fig. 5). The readings are again slightly influenced by the variations in the water level. The data from further profiles presented by Boháč and Škopek (2004) indicate that the active zone is confined to the upper 20 metres of the landfill.

The dissipation of excess pore water pressures under the embankment is shown in Fig. 6. The maximum excess pore pressures were measured a few days after the completion of the embankment. The highest measured values were even higher than the surcharge caused by the embankment (145kPa). It indicates, that additional excess pore pressures

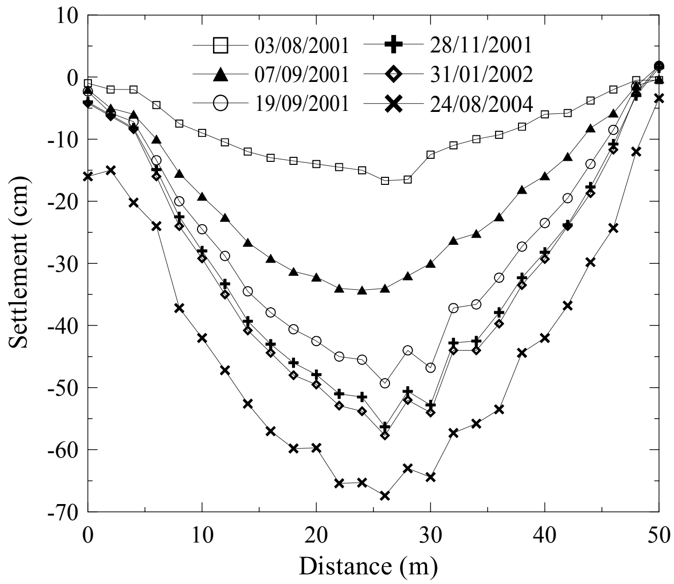

Fig. 3. Hydrostatic levelling profile 1.

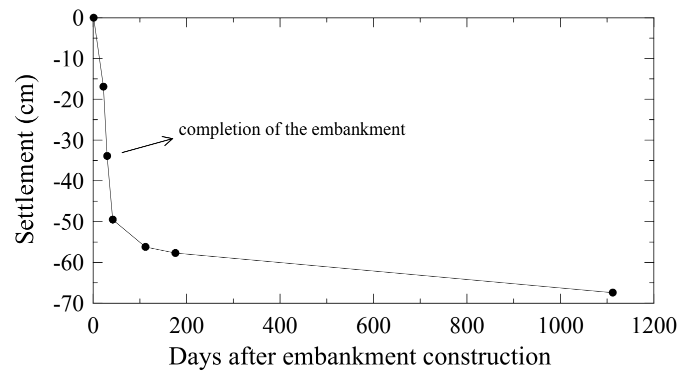

Fig. 4. Surface settlement in the centre of the trial embankment (profile 1).

were probably generated by compaction during construction of the embankment. The lowering of water level in 2003-2004 might be the cause of non steady values of pore pressures even after 500 days after the embankment construction.

CENTRIFUGE MODELLING

The results of the monitoring of the trial embankment indicate that the behaviour of the landfill is highly variable. The measurement of hydrostatic levelling profiles revealed that significant differential settlement can be expected. A similar conclusion about landfill compressibility was reported also for example by Dykast (1993) and it seems a typical feature of the landfills. The differential settlement can be caused by variations in intergranular porosity. The initial volume of interlump voids during the landfill construction can vary due to different shapes of the lumps and their size distribution or the filling method. It is also difficult to determine the age of the landfills because of gradual construction lasting several years. Unfortunately there is usually poor information about the landfill construction, existence of drainage at the bottom of

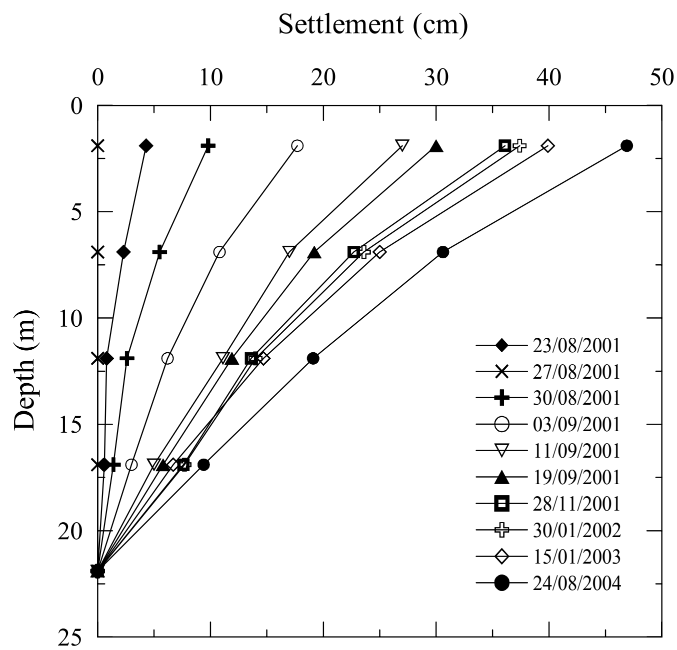

Fig. 5. Settlement of depth reference points.

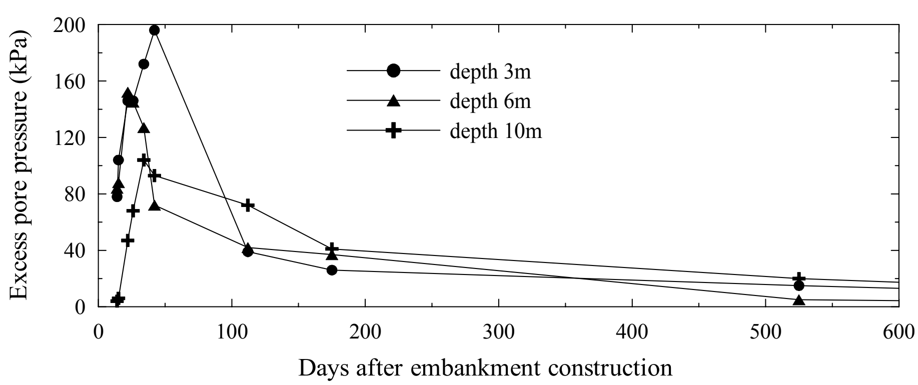

Fig. 6. Excess pore pressures after the construction of trial embankment.

the landfill, etc., so that the initial conditions are generally unknown and particular information cannot be generalised.

The main advantage of the centrifuge modelling is that the whole process of the consolidation can be simulated in a short time and there is a perfect control over the initial conditions. Centrifuge modelling of the case history from Northern Bohemia can be carried out with similar instrumentation as was installed in situ. The geotechnical centrifuge had never previously been used for the modelling of the Czech landfills and it can broaden the information available to us about the behaviour of double porosity clay.

Centrifuge modelling was carried out at ETH Zürich in Switzerland. Because of a lack of previous experience of centrifuge modelling of these landfills, a small centrifuge was chosen for preliminary tests. Small centrifuge tests included parametric studies of the influence of the shape of clay lumps and their size distribution on the intergranular porosity. Other laboratory techniques were used for further investigation of the centrifuge models so that the degradation of the structure in vertical profile of the landfill could be analysed. A technical note with the results of these preliminary tests is in preparation (Najser et al., 2008).

The modelling of the trial embankment on the consolidated landfill was carried out in the geotechnical drum centrifuge. The centrifuge scaling laws (Taylor, 1995) were applied for the centrifuge modelling. Consolidation time was scaled by n^2 and all dimensions were scaled by n, where n is the scale factor of the g level at the effective radius during centrifuge tests. 'Prototype' properties referred in this paper were calculated from the model parameters using the appropriate scaling law.

ETH Zürich drum centrifuge

A detailed description of the ETH drum centrifuge has been written by Springman et al. (2001). The diameter of the drum is 2.2 m and maximum acceleration 440 g. The models were prepared in square containers (400x400 mm in plan, 200 mm high) which were mounted into the drum before the test. Figure 7 shows a simple sketch of the centrifuge with one container and instrumentation for the test. The second container was placed on the opposite side of the drum as a counterweight. In the central part of the centrifuge, there is a tool platform with a pair of multipurpose actuators. This tool platform can be joined with the drum to rotate at the same speed, but it can be also accelerated/decelerated separately from the drum. Radial and tangential motion of each actuator can be controlled during the flight. As shown in Fig. 7, a laser measuring device was mounted on the actuator to measure vertical deformation of the model during flight.

Preparation and instrumentation of the model

The clay from the North Bohemian landfill area was air dried at 50°C and crushed between two metal platens. The size distribution of the lumps required for the test was obtained by sieving. The alternative technique of preparing of wet clay lumps from the slurry described by Leung et al. (2001) was not suitable due to the targeted lump size distribution and irregularly shaped lumps. Dry crushing of clay lumps was also thought to preserve the stress history of the lumps. No information on lump size distribution of the landfill at the site of the trial embankment was available. Therefore data from similar landfills (presented by Dykast, 1993) was considered for the centrifuge model. The full line in Fig. 8 shows the prototype lump size distribution used for the centrifuge test. Dashed lines represent the literature field data. Before the test, dry lumps were poured into the container in four layers. The pore pressure transducers were installed between the layers (corresponding approximately to ¼, ½ and ¾ of the model depth).

The main goal of centrifuge modelling was to simulate the case history and to take the same type of measurements as in situ, to be able to compare them. The centrifuge model was therefore instrumented similarly to the trial embankment subsoil. The vertical deformation of the landfill was measured by a laser mounted on the tool platform actuator. It scanned the model in three profiles at selected time intervals. After construction of the embankment, the deformation of its surface was measured in the same way.

The pore pressure was measured with Druck PCDR81 pore pressure gauges (10 mm long and 6 mm in diameter) installed during the model construction. The gauges were not fixed and they could move freely with the soil. Similarly to the field, pore pressures were measured between the lumps. Due to the similar dimensions of the lumps and transducers, no pore pressure gauges could be installed inside the lumps. In total, 6 transducers were located in three horizontal levels and two vertical profiles. The first profile was installed under the

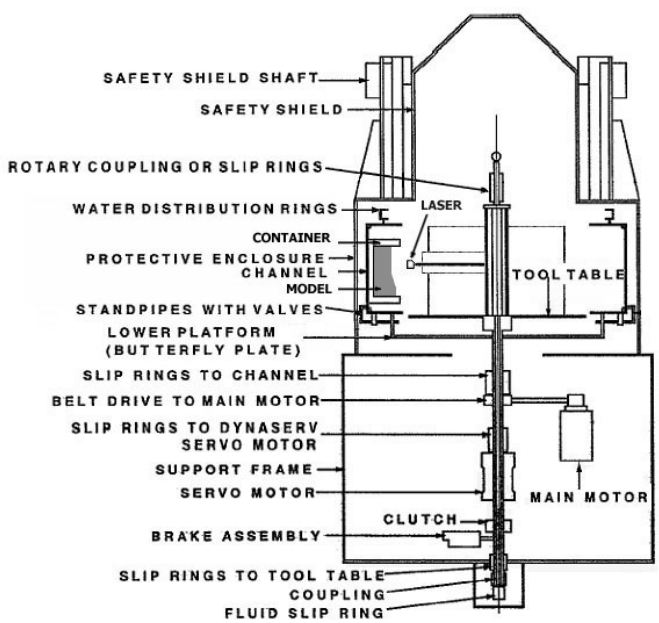

Fig. 7. Sketch of drum centrifuge at ETH Zürich (modified after Springman et al., 2001).

embankment (3b in Fig 9) while the second one was under "far-field" conditions (3a).

A new tool called "system of straws" was developed for measuring the deformations at different depths. The straw is composed of a thin aluminium rod and two discs, one at the top and one at the bottom of the rod. In pouring the lumps in the container, straws were built in the model in the vertical position with the bottom discs at different levels. The rod was lubricated with silicon grease to reduce friction between their surface and the soil. The straw could freely move during the test according to the position of bottom discs, which moved with the surrounding soil. The top disc was above the model surface and the change of its position was measured with a laser transducer mounted on the actuator so that it could be moved in all directions as required to carry out the scanning.

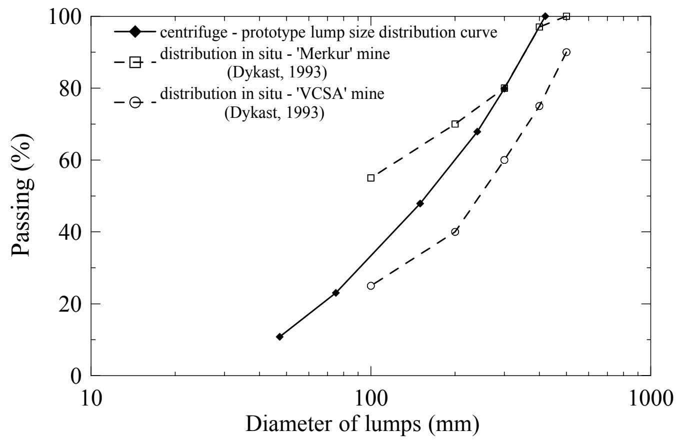

Fig. 8. Comparison of prototype lump size distribution curves with field data.

Test procedure

The landfill model was prepared in the container outside the centrifuge. After construction, the model was partly flooded to create suction to keep the model stable during installation to the centrifuge. The container was then rotated through 90° and bolted onto the centrifuge drum (Fig. 7). The centrifuge was then accelerated to 20 g and the lumpy clay layer was flooded in flight through the water supply system. During the whole test, the groundwater level was kept constant, close to the model surface. After full saturation, the model was accelerated to 150 g. During consolidation, the surface deformation and pore pressures were monitored. When constant values were reached, the embankment was constructed on the top of the landfill. Two different techniques were considered: in-flight construction and stationary construction at 1 g. An advantage of in-flight construction of the embankment is that the same stress history as in situ is achieved, because the centrifuge can rotate for the whole test. The embankment is constructed from lead balls poured through the filling tube mounted on the tool platform. This method was described by Weber et al. (2006). Unfortunately the in-flight filling technique is limited to a g-level up to 50 g, which is not sufficient for modelling the case history in question with its real geometry. The maximum prototype height of the landfill at 50 g corresponds to 6 metres. For modelling a 20 m high landfill, the centrifuge test should be carried out at 150 g. Therefore the centrifuge had to be stopped after consolidation of the model and the embankment was constructed at 1 g from wet sand. The centrifuge was then re-accelerated. Experimental data from the preliminary tests and geotechnical centrifuge tests suggest that

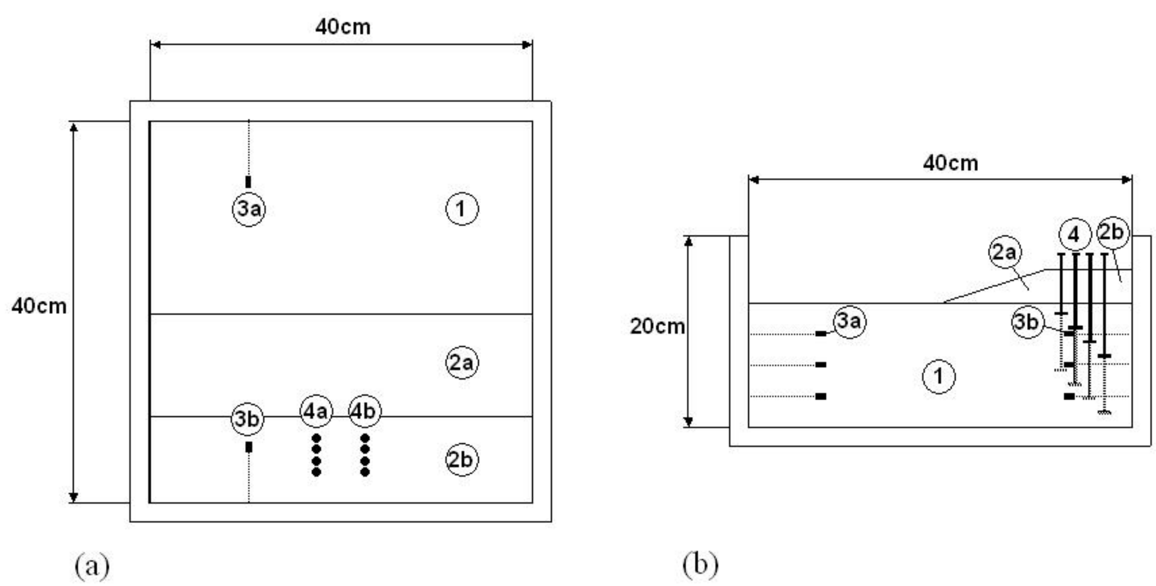

Fig. 9. Centrifuge model and its instrumentation -(a) plan view, (b) cross section (1 – landfill, 2a – embankment slope, 2b – embankment crest, 3 – pore pressure transducer profiles, 4a – straws with bottom discs in the top part of the landfill, 4b – straws in the bottom part of the model).

the error caused by unloading and reloading of the model may not be significant in comparison with large deformations typical for the double porosity soil. After the embankment construction, pore pressures and surface deformation were monitored again until steady values were measured.

In the following section, test results of two centrifuge tests carried out at 150 g are discussed. The results of the test at 50 g with in-flight construction of the embankment have been presented elsewhere (Najser, 2007; Pooley et al., 2007).

CENTRIFUGE TESTS RESULTS AND DISCUSSION

Pore pressures

The centrifuge models were drained at both the top and bottom of the lumpy soil layer. Figure 10 shows the distribution of pore pressures after application of the embankment surcharge. The lines correspond to different times after embankment construction (noted in legend). Profile B (full symbols) represents the pore pressure transducers under the embankment. Profile A was not significantly influenced by the embankment surcharge. The maximum values of excess pore pressures correspond to the time it took the centrifuge to accelerate after embankment construction and demonstrate the special behaviour of double porosity soil. The highest increments of pore pressures were measured by the lowest transducer, although the drainage path was half that for the transducer located in the middle of the sample. Further the slowest rate of pore pressure dissipation can be observed in the bottom part of the model. This can be explained by the closing of interlump voids during self-weight consolidation as a result of high vertical stress in the bottom part of the model. The permeability of the lower part of the model is therefore reduced to the permeability of the clay, which is very low. In

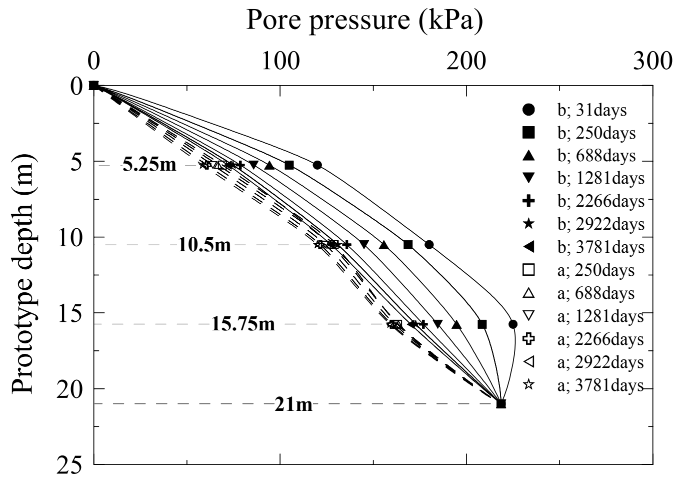

Fig. 10. Pore pressures after the embankment construction.

the top half of the model, the double porosity structure is preserved and water can drain upwards faster through the open interlump voids. These preferential drainage paths have the effect of allowing a high permeability even in the middle part of the model.

A comparison of the dissipation of excess pore pressures in the field and in the centrifuge model is presented in Fig. 11. The maximum excess pore pressures were measured after 30-40 days in the prototype, which corresponds to the time of completion of the trial embankment. As mentioned above, additional excess pore pressures were generated by the embankment compaction, so the maximum values cannot be directly compared to the centrifuge test. After 100 days, centrifuge and field data reach similar values and also the rate of the dissipation is similar.

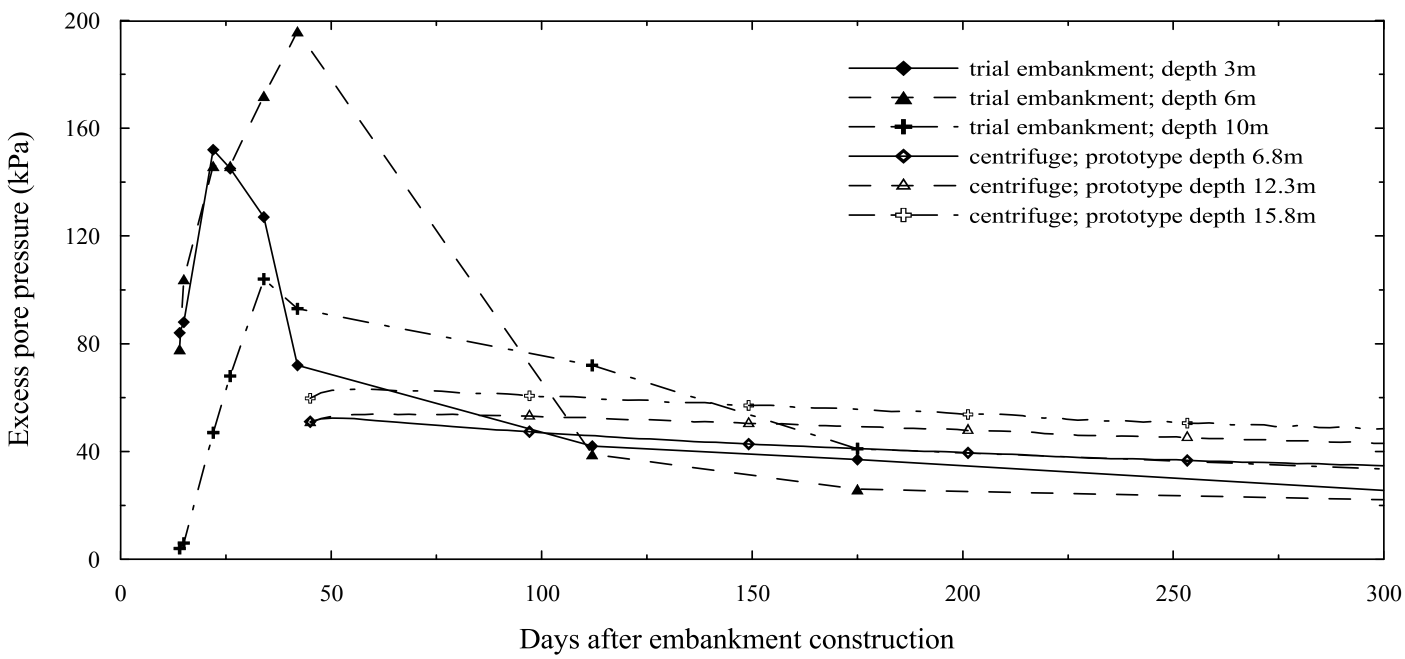

Fig. 11. Comparison of dissipation of centrifuge test and field excess pore pressures after embankment construction.

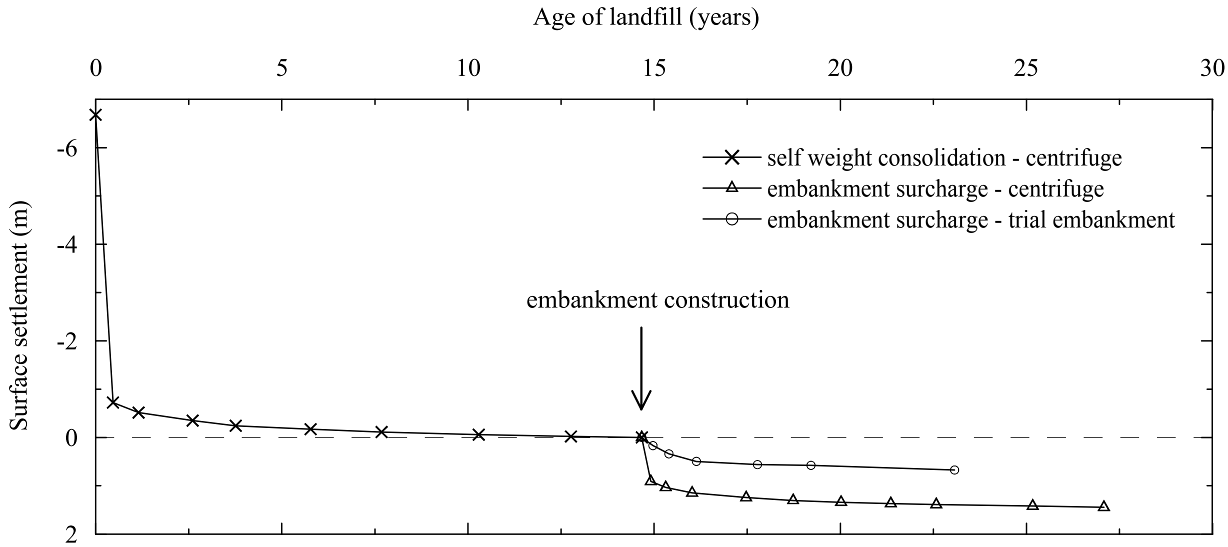

Fig. 12. Comparison of landfill surface settlement.

<u>Surface deformations</u>

The deformation of the landfill surface, and its comparison with the hydrostatic levelling profile 1, is presented in Fig. 12. The centrifuge data are plotted from the beginning of self-weight consolidation. Zero settlement refers to the end of self-weight consolidation before the embankment construction, when the first in situ measurements were carried out. The first part of the self-weight consolidation curve exhibits rapid settlement, which is followed by a slow subsequent deformation until 15 years at the prototype time scale. A similar shape of the consolidation curve with rapid initial settlement was measured after application of the surcharge. Similar consolidation curves were measured also in situ. When compared to the field measurements, the centrifuge model exhibits larger settlement. This could be due to a different interlump porosity at the time of embankment construction. This difference in intergranular porosity can be explained by different conditions in situ, where the top layer of the landfill is exposed to the rainfall and climate effects. Due to weathering, clay lumps are decomposed and interlump spaces are partly filled with clay. In the laboratory however, weathering does not occur and the porosity of the soil remains higher.

<u>Depth reference points</u>

Figure 13 shows a comparison of the deformation of depth reference points in situ and the straws in the centrifuge model. The presented settlement corresponds to 656 days for the prototype after embankment construction. The surface settlement for both data series is also presented. The settlement in the lower part of the model is similar to in situ data. The interlump voids are mostly closed at depth because of high overburden pressure during the self-weight consolidation. In the upper part of the model, the deformation is greater due to the higher interlump porosity compared to the field. These findings are in line with the previous interpretation of surface deformation measurements. The scatter of the centrifuge straws data was due to the fact that measurement inaccuracies were relatively large compared to the small absolute movement of the straws.

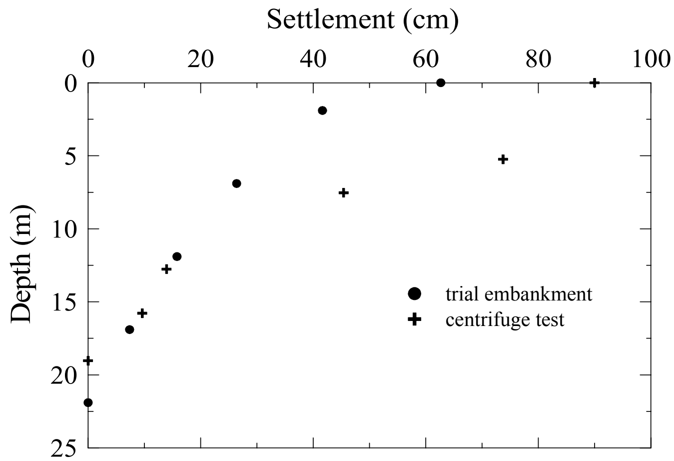

Fig. 13. Settlement of depth reference points.

Deformation of the centrifuge model at various depths has recently been studied at ETH Zürich using the particle image velocimetry (White et al., 2003). The first results have been presented by Pooley et al. (2007).

CONCLUSIONS

In situ measurements on a trial embankment showed high and non-uniform compressibility of the 20-30 year old landfill. After the application of a surcharge, the landfill exhibits large initial settlement followed by small deformations accompanied by creep.

The centrifuge modelling showed that permeability of the soil is controlled by its complex structure. The double porosity structure creates preferential drainage paths and accelerates the consolidation of the soil. When interlump voids are closed, the dissipation of excess pore pressures is much slower being controlled by permeability of the clay. Similarly to the field measurements, the settlement curve due to the embankment surcharge shows a large initial deformation, which is probably caused by fast pore water drainage through the open interlump voids.

Centrifuge modelling of the case history presented an excellent opportunity to replicate several decades of behaviour within one day. Results showed smaller deformations occurred in the top 10 metres of the landfill in comparison with the centrifuge model. This could be partly influenced by a reduction of the porosity during compaction of the embankment in-situ and partly due to climate effects, which may have caused faster degradation of the soil structure.

ACKNOWLEDGEMENT

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