Assessment of the use of dynamic compaction on double porosity clay landfill

Evaluation de l'emploi du compactage dynamique sur remblai d'argile à double porosité

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ABSTRACT

Open cast coal mining in Northern Bohemia produces overburden waste of overconsolidated clay lumps that are placed in spoil heaps or used as backfill in exploited mines. This forms landfills with a double porosity structure consisting of voids between lumps (inter-granular) and voids within lumps (intra-granular). The total porosity can be up to 70 %, making the soil highly compressible even after self-weight consolidation. Soil behaviour is characterised by large absolute and differential settlements. Dynamic compaction is one of the ground improvement methods used before construction on these clay landfills. Model tests on scaled double porosity clay landfills were carried out in the ETH Zurich drum centrifuge. A period of self-weight consolidationwas followed by in-flight dynamic compaction. To assess and compare the strength of the clay fill, in-flight displacement-controlled rigid foundation tests were carried out on the centrifuge models. The total load on the foundation, and pressure distribution under it, were measured.

RÉSUMÉ

Les mines de charbon à ciel ouvert produisent des déchets sous forme de blocs d'argile surconsolidée qui sont entreposés en décharge ou utilisés comme matériau de remplissage dans les mines exploitées. Ceci forme des remblais avec une structure à double porosité consistant en vides entre les blocs (inter-granulaire) et à l'intérieur des blocs (intra-granulaire). La porosité totale peut atteindre 70 % rendant le sol hautement compressible même après consolidation sous poids-propre. Le comportement du sol est caractérisé par des tassements absolus et différentiels importants. Le compactage dynamique est une des méthodes d'amélioration des sols utilisée avant de construire sur ces remblais d'argile. On a procédé à des essais dans la centrifuge à tambour de l'ETH de Zurich sur des remblais d'argile à double porosité. Après une période de consolidation on a réalisé un compactage dynamique en vol. Pour évaluer et comparer la résistance du remblai d'argile on a effectué en vol des essais de chargement d'une fondation rigide à déplacement contrôlé. La charge totale de la fondation et la pression sous celle-ci ont été mesurées.

Keywords : Dynamic Compaction, Lumpy Soils, Fills, Centrifuge Modelling

1 INTRODUCTION

Open cast clay mining in Northern Bohemia in the Czech Republic has been taking place for over 60 years. The overburden material of overconsolidated clay lumps is deposited in disused mines leading to fills with double porosity structures consisting of two types of voids, the inter particle voids inside the overconsolidated lumps and the intra particle voids between the lumps. The overall void ratio can reach up to 70% (Feda, 1998). Due to the deposition method, changes in the groundwater table and subsequent self weight consolidation, the fill is generally very inhomogeneous (Figure 1), leading to large absolute and differential settlement in the field. When a new motorway between Prague and Dresden was designed to cross this area, which covers over 100 km^2, there were significant challenges to ensure adequate foundations.

Figure 1. Fresh landfill. (photograph M. Větrovský)

Dynamic compaction is one of the ground improvement techniques used in the field (Barvinek, 1986) to reduce the settlement under such constructions. Dynamic compaction provides an impact energy, which increases the soil density by fracturing lumps to fill the intra particle voids, or by deforming the lumps.

Centrifuge modelling of the behaviour of fills consisting of lumpy clays has been carried out in the 2.2 m diameter geotechnical drum centrifuge at ETH Zürich in Switzerland (Springman et al., 2001). Clay lumps from the North Bohemian area (e.g. as described by Dysak, 1993) were scaled from field size inversely with g-level. Thus for a centrifuge model at 50g, the maximum clay lump diameter of 50 cm should be scaled down to 10 mm. The fills have been modelled first to study the settlement behaviour under self weight in order to identify the various processes leading to the increased deformation and (e.g. Pooley et al., 2007) in order to model the behaviour of two test embankments. Subsequently different ground improvement techniques have been investigated, starting with the use of sand compaction piles (Pooley, et al. 2008a).

Physical modelling of dynamic compaction has been incorporated into this research work. The methodology applied will be introduced, and results such as the development of pore water pressures during compaction will be presented. An axisymmetric footing test was carried out on the improved soil.

2 DYNAMIC COMPACTION TOOL

Dynamic compaction has to be carried out in flight to model stress levels in the soil correctly. This required the development

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of a dynamic compaction tool, which was based on a rockfall tool developed by Chikatamarla et al. (2006a), relying on a magnet holding a weight and dropping it in the right place on demand. After reaching the required g-level, the magnet is switched off and a metal weight falls in the direction of the model. The weight has to be guided in order to keep the falling weight in contact with the rotating machine so that the weight remained in the g field so that the scaling benefits could be applied to the compaction process.

The rockfall tool had to be adjusted to the requirements of repeated compaction, as the falling weight needed to be collected by the tool again while the model was still under prototype stresses in flight, in order to be released again. To accomplish this, a slotted chute was used. The arrangement of the dynamic compaction tool is shown in Figure 2. The model weight is connected to the magnet. When the magnet is switched off, the falling weight moves downward in the chute and hits the soil with a portion of the tool remaining in the chute. The magnet is connected to the actuator piston, while the chute is connected to the housing of the actuator. The piston of the actuator can be driven through the chute and switching on the magnet allows it to pick up the weight and move it back to the starting position. The slot allows the magnet to be positioned to pick up the weight.

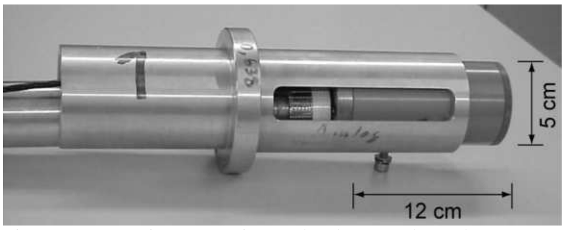

Figure 2. Dynamic compaction tool. (photograph Markus Iten)

However, various features of the model scale differently: where g-level is n, the model size (and lump size) are also scaled by n, so that 0.5 m lump sizes are reduced to 1 cm maximum size at 50g. n is determined from a nominal radius r from the centre of the centrifuge, the angular velocity, ω, and earth's gravity g, whereby $ng = \omega r^2$ provided that r and ω remain constant. Consolidation processes speed up by n^2 since the pore pressure increases remain constant in model and prototype whereas the term representing the drainage path, which is squared, is then n^2 smaller According to standard scaling laws, prototype energy is n^3 times the model energy (Schofield, 1980). As dynamic compaction is modelled with a falling weight, which has changing radius relative to the centre of rotation of the centrifuge, its effective radius is smaller than for the soil model, leading to slightly lower n values than usually taken as the nominal value. Details of these scaling relationships can be found in Chikatamarla et al. (2006b). The mass m of the falling weight was 0.339 kg and the tool allowed a maximum fall height h of 150 mm. For simplification, the input energy is defined here by m x g x h and scaled by n^3.

3 PHYSICAL MODELLING OF DYNAMIC COMPACTION ON LUMPY SOILS

Two soil samples were prepared in parallel, to be installed diametrically opposite to each other in the ETHZ geotechnical drum centrifuge. Figure 3 shows the arrangement of the two sample containers (A & B) in the centrifuge, with the actuator tower sitting on a tool table in the centre of the centrifuge. Two actuators can move radially, vertically and around the circumference in tandem, to apply either force or displacement controlled perturbations, and so that the tower remains fully balanced even while it is rotating during the experiment.

The soil models were prepared outside the centrifuge by placing clay lumps in the containers to a depth of 15 cm (Figure 4), which were partially saturated and preloaded to be able to rotate them through 90° to position them in the drum centrifuge with minimum disturbance. Thereafter, the centrifuge was accelerated to 20g, whereupon water was supplied to the container so that the samples became fully saturated. The centrifuge was sped up to a nominal acceleration field of 50g. This situation was maintained for approximately 5 hours to represent a prototype consolidation time of 1 year and 5 months. The settlement after this period of consolidation under self weight was typically 14 cm. This procedure was similar to other variations studied on lumpy soils (Pooley et al., 2007; Pooley et al., 2008b; Najser et al., 2009).

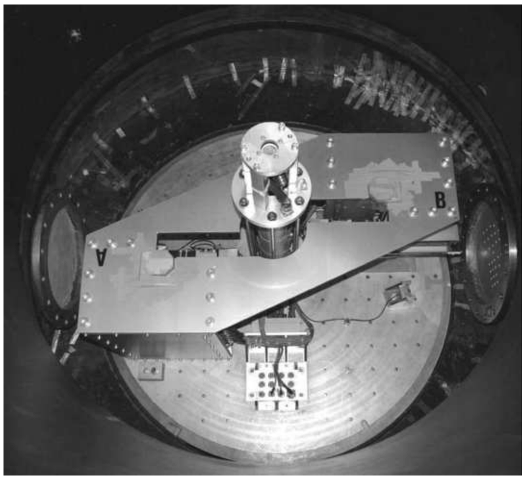

Figure 3. Drum centrifuge (2.2 m drum diameter) arrangement

Figure 4. Placement of dry model lumps in the cylindrical container, 40 cm in diameter (photograph Jan Najser)

The centrifuge was stopped after consolidation, the dynamic compaction tool (DTV) was fitted to the actuator and a geotextile was placed on soil surface. The DTV was not fitted earlier for safety reasons, since small fluctuations in the current could have caused the weight to be released at an earlier stage. The geotextile was placed on top of the lumpy soil to prevent the dynamic compaction tool from penetrating into the lumpy soil too deeply.

Even using the geotextile, DTV tests were only possible at the nominal level of 20g acting on the soil in the container, when using the existing setup, due to the restricted force transfer of the magnet. The limiting factors for the DTV are given by the forces acting on the weight in the pick up phase. The magnet has to resist the centrifugal force on the weight, plus the additional friction at the sides of the weight, friction in the chute and suction forces at the base of the falling weight. Thus, the authors decided to conduct dynamic compaction under smaller energies at an acceleration level of 20g, varying the fall height according to Table 1, even though these energy levels are not comparable to those used in the field (e.g. 1 tonne dropped from 10 m resulting in a 100 kJ prototype dynamic compaction event).

Table 1. DTV boundary conditions

Test	Fall height (model scale)	Approximate input energy (prototype scale)
3.2_dtv model A	60 mm	1.6 kJ
3.2_dtv model B	100 mm	2.7 kJ
5.1_dtv model A	80 mm	2.1 kJ
5.1_dtv model B	120 mm	3.2 kJ

Figure 5. Falling weight resting on geotextile after 10 impacts at 20g

Figure 6. Close view on the impacted area

After installation of the DTV tool and the geotextile, the centrifuge was re-accelerated to 20g. Then 10 impacts were applied to one position on top of the lumpy soil model. The centrifuge was stopped again after these impacts (Figure 5) and both the DTV tool and geotextile were removed from the sample, whereupon a cylindrical cavity created by the dynamic compaction was visible, and crushing of the lumps was observed by inspection (Figure 6). The hole was filled by hand with partially saturated sand and the foundation tool, including a tactile pressure sensor (Springman et al., 2002) was connected to the actuator to measure the stress distribution under the footing. Footing tests were conducted at 50g using a stiff circular foundation with a diameter of 56 mm representing a prototype diameter of 2.8 m. The footing tests were displacement controlled at a radial displacement rate of 0.02mm/sec at model scale.

4 RESULTS

The data available from tests is reviewed to enable the effect of dynamic compaction events to be studied. Visual inspection showed local compaction of the soil strata.

Pore water pressure measurements were available during the dynamic compaction event by means of data obtained from pore pressure transducers (PPTs), of type Druck PDCR81, that had been placed in the model during construction. One profile of 3 PPTs was placed close to the area of dynamic compaction and the foundation test ("near field"), and a further 2 PPTs were installed as far away from the foundation test as possible ("far field"). The PPTs were placed one above each other at roughly 3 heights in the model: ¼, ½, and ¾ of model height in the unsaturated lumpy clay models. Since the PPTs were free to move with the soil, their depth below the phreatic surface changed during the test. The results of test 3.2_dtv model B are presented in Figure 7.

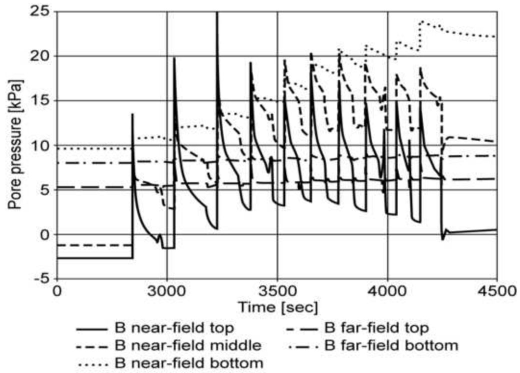

Figure 7. Pore pressure variations during 10 impact events for 3.2_dtv model B, with nominal 2.7 kJ impact energy

Figure 7 shows that the pore pressures measured local to the impact crater are raised by DTV. The data show a brief peak in pore pressure on every impact, most pronounced in the near field and at the surface, with decreasing peaks with increasing depth of the PPT. It also shows an accumulation of increasing pore water pressure, mainly for the readings of the PPTs located in the near field at greater depths. This indicates that the compaction causes significant volume changes in the sample, leading to a major reduction of the intra-granular voids, presumably through plastic deformation of the lumps. This leads to greatly reduced macro-permeability so that as depth in the model increases, the drainage path gets longer and the increased pore pressure is less able to dissipate. In comparison, the pore pressure spike on impact is greatest near the surface but it dissipates fairly rapidly because of shorter drainage paths to the surface. Examining the near-field top and middle PPTs, a pore pressure accumulation can be observed for the first 8 impacts but then both the extent and absolute magnitude of the peak drops off, which might be related to increase of macro-permeability once more through development of surface cracks or fracturing in the model.

Further information about the efficacy of dynamic compaction is gained from foundation tests conducted after the DTV. The cavities were filled with unsaturated sand, which was flattened to obtain a 'flat' interface without local contact points. To avoid damage to the tactile pressure sensor, the foundation was not displaced beyond 20 mm into the soil, and at this limited displacement, failure was not visible in any of the tests.

Figure 8 shows the net soil pressure-displacement distributions for the 4 footing tests conducted on top of the zone of dynamic compaction. The pressures mobilised in the ground correlate well with the impact height, i.e. the soil response is stiffer when impact energy from dynamic compaction is higher. Doubling the impact energy from that applied to the 3.2_dtv model A (1.6 kJ) to the 5.1_dtv model B (3.2 kJ), when comparing the foundation response at a displacement of 15 mm at model scale, results in an increase of net soil pressure acting on the foundation of 25% (160 kPa to 200 kPa). In comparison, a foundation test on unimproved ground under similar boundary condition reached for a deformation of 15 mm when mobilising a net soil pressure of approximately 60 kPa (Pooley et al., 2008).

The stress distribution measured under the foundation confirms this behaviour. Figures 9 and 10 show the stress distributions measured with the tactile pressure sensors at the ultimate deformation applied. Both show stress concentration around the edge of the foundation as expected. The stress distribution under the centre of the foundation is very different between the models 3.2_dtv model A (Figure 9) and 3.2_dtv model B (Figure 10). For the model compacted with lower impact energy, unloaded areas in the centre of the foundations are visible. Local stress concentrations in this area might be caused by uneven filling of sand in the cavity, but are probably related to the presence of any remaining intact lumps underneath the footing. The model compacted with higher impact energy shows that the soil is stiffer as the ground under the foundation is almost completely activated and the load distribution is more uniform, indicating that most lumps were deformed or crushed to give a more homogeneous soil deposit under the loaded area.

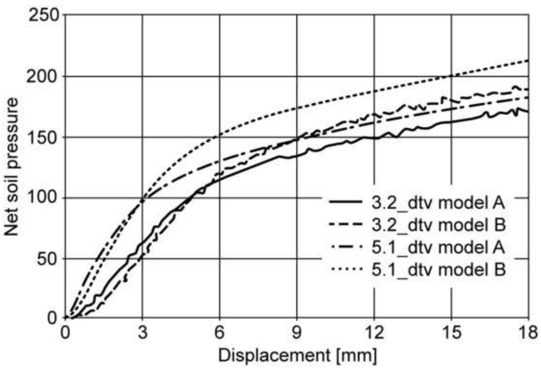

Figure 8. Net soil pressure-displacement curves for foundations tested after dynamic compaction

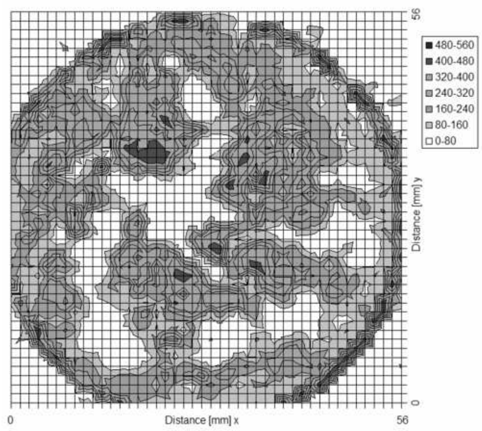

Figure 9. Stress distribution at displacement of 18 mm in the test 3.2_dtv model A

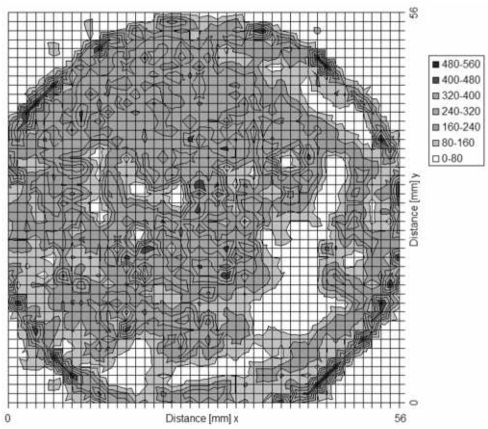

Figure 10. Stress distribution at displacement of 18 mm in the test 3.2_dtv model B

5 CONCLUSIONS

The test results presented here show a good correlation between compaction energy and resulting soil stiffness. Significant punching settlement indicates a reduction of porosity below the compacted area. An associated reduction in permeability can be assumed to follow based on the pore pressure measurements. Possible formation of tension cracks and fractures could be interpreted from the measurements, but could not been verified after the test. Although the effect of dynamic compaction on single lumps (deformation, fracturing, crushing) could be discussed in a qualitative fashion, it was not directly quantified.

With this paper, the authors also demonstrated that physical modelling of dynamic compaction could be achieved. Unfortunately, it was not possible to model correctly the impact energies imposed in the field within the boundary conditions associated with the centrifuge and the tool. However, the latter could be improved chiefly by using a stronger magnet, in order to be able to overcome the gravitational forces, suction and friction when retrieving the compacting weight.

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