Back-Analysis of Weathering Destructuration of a Lumpy Clay Fill

J Najser
Charles University in Prague, Faculty of Science, Czech Republic (jannajser@centrum.cz)
D Mašín
Charles University in Prague, Faculty of Science, Czech Republic (masin@natur.cuni.cz)
J Boháč
Charles University in Prague, Faculty of Science, Czech Republic (bohac@natur.cuni.cz)

ABSTRACT The hypoplastic model for clays with meta-stable structure was used in modelling the behaviour of two instrumented trial embankments on a lumpy clayfill. The model parameters were calibrated using isotropic and shear triaxial tests on the reconstituted clay and oedometer tests on the specimens prepared from the scaled-down clay lumps. The numerical simulations gave four times higher settlements than the field data due to the degradation of the double porosity structure in the landfill in-situ. The weathering destructuration was included in the model, which improved the simulations dramatically.

INTRODUCTION

Open cast mining of brown coal has been taking place in Northern Bohemia (north-western part of the Czech Republic) for more than 60 years. The overburden consists of Tertiary clay and claystone of high plasticity. The average porosity of the clay is 40%, the 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 25% quartz. Overburden is excavated during the mining process and placed into large spoil heaps outside the mines as irregularly shaped clay lumps of diameter from a few millimeters up to 0.5 m. Mine pits are also backfilled with the excavated soil after exploitation. The thickness of the internal fills can reach 200 m. The total area of clayfills exceeds 100 km^2.

The key feature of the clayfills is their double porosity structure, consisting of intragranular (voids within the clay lumps) and intergranular (macrovoids between the clay lumps) porosity. The total porosity of the fresh fill can be up to 70% (Feda 1998). Soon after filling, the soil can be described as a “granular” material. Over time, the landfill structure changes and the behaviour resembles a fine-grained material. However, even 20-30 years after filling, the soil is not homogeneous and double porosity structure remains. Old landfills exhibit high and non-uniform compressibility, wetting collapse potential (Charles 2008) and provide a real challenge for geotechnical design.

IN SITU DATA

Two trial embankments were built at a site, where a backfilled mine pit had been used as a fly ash lagoon. The thickness of the clayey fill was 30 m and the age of the landfill was 20-30 years at the time of construction. Embankments were monitored for 3 and 5 years respectively.

Embankment 1 was constructed in a location, where 3.5 m thick permeable layer of fly ash had been deposited on the top of the landfill. The embankment was 6 m high (generated vertical stress of 108 kPa) with crest dimensions 35 by 4.5 m and slopes graded at 1:1.5. Ground water level was close to the surface during the monitoring (Fig. 1). Embankment 2 was constructed on 1.4 m thick rubble layer (no fly ash was present under the embankment). It was 7.5 m high (vertical stress at the base 132 kPa) with crest dimensions 20 by 35 m with slopes graded at 1:1.5. Ground water level was close to the surface, but it decreased to 5 m below the landfill surface during the time of monitoring (Fig. 1).

Both embankments were instrumented by hydrostatic levelling profiles, pore pressure gauges and depth reference points in the embankments' subsoil. Detailed description of the monitoring and discussion of the results can be found in Škopek (2001) and Škopek & Boháč (2004).

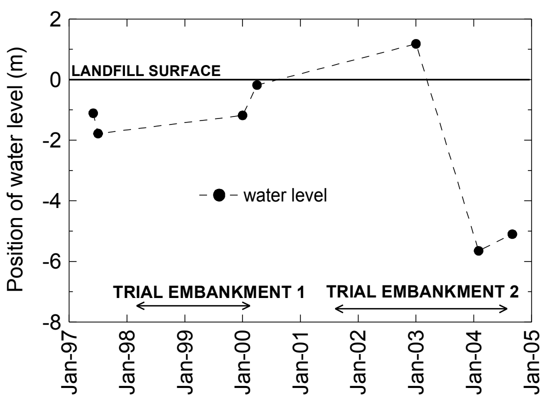

Fig. 1 Ground Water Level Variations during Monitoring of Embankments.

NUMERICAL MODEL

A hypoplastic model for clays was developed by Mašín (2005). The model requires 5 parameters, similar to the parameters of Modified Cam Clay model, which can be easily calibrated from the results of isotropic compression test and triaxial shear test: N and λ^* define the position and slope of NCL, κ^* represents the slope of the swelling line, φ_c is the critical state friction angle and r characterizes soil shear stiffness.

The hypoplastic model for clays with meta-stable structure (Mašín 2007) was developed to describe the behaviour of structured clays and can be applied for modelling of double porosity clays. The model assumes one additional state variable – sensitivity and requires three additional structure parameters, describing the rate of structure degradation (k), final sensitivity (s_f) and damage strain rate parameter (A).

MODEL CALIBRATION

Laboratory experiments used for calibration of the constitutive model were carried out on samples from the "5. květen" landfill located near the trial embankments. Parameters φ_c and r were calibrated from the results of undrained triaxial shear tests on reconstituted clay (Fig. 2).

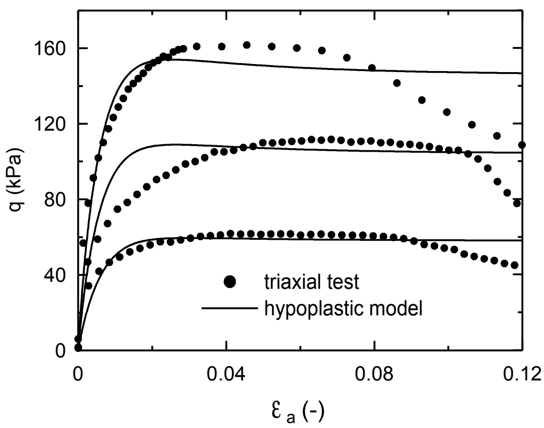

Fig. 2 Calibration of Model Parameters φ_c and *r*.

The position and slope of NCL were determined from isotropic compression tests on the reconstituted clay carried out by Hájek et al. (2009). The parameters of the soil structure were determined from a set of oedometric compression tests on the granulated clay, which represented a scaled down model of the lumpy clay landfill. Details about the laboratory experiments and preparation of the specimens are given in Najser et al. (2009). Fig. 3 shows the compression of both reconstituted and lumpy clay and the prediction by the hypoplastic model for clays with meta-stable structure. The calibrated parameters of the numerical model are summarized in Table 1.

TABLE 1. The Parameters of Hypoplastic Constitutive Model for Clays with Meta-Stable Structure.

φ_c	λ^*	κ^*	N	r	k	A	s_f
22.4	0.0835	0.0187	1.045	0.3	0.28	0.25	1

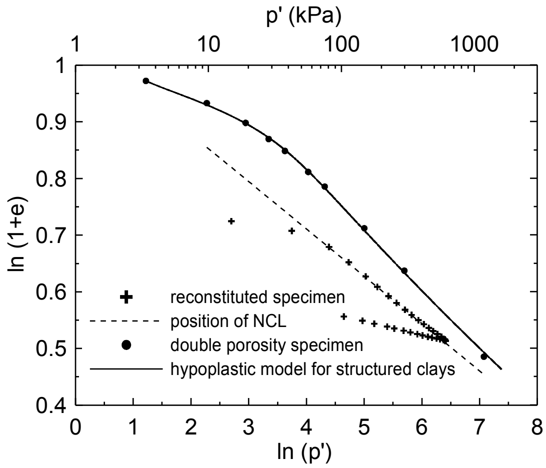

Fig. 3 Calibration of Constitutive Model on Compression Tests of Reconstituted and Double Porosity Specimens.

The performance of the model was assessed by a comparison of a self-weight consolidation of the fresh landfill in a centrifuge test (no data are avilable from the field) with the numerical model prediction. The centrifuge test was carried out at ETH Zürich geotechnical centrifuge (Springman et al. 2001) and the test was described in detail by Najser et al. (2010b). The soil for the centrifuge model was prepared by crushing of air dried landfill material, and the required lump size distribution was obtained by sieving. The lumps were poured into the centrifuge container and fully flooded before the start of the test. The centrifuge test was carried out at 150 g and represented a 15 years long self-weight consolidation of a 28.5 m high landfill in the prototype scale. Figure 4 shows a good correlation between the centrifuge test settlement curve and the finite element consolidation analysis using the hypoplastic model. Permeability linearly dependent on landfill depth with k = 5*10^{-8} m/s at σ_v' = 5 kPa and 1*10^{-10} m/s at σ_v' = 150 kPa was chosen for the numerical modelling based on back analysis of centrifuge models.

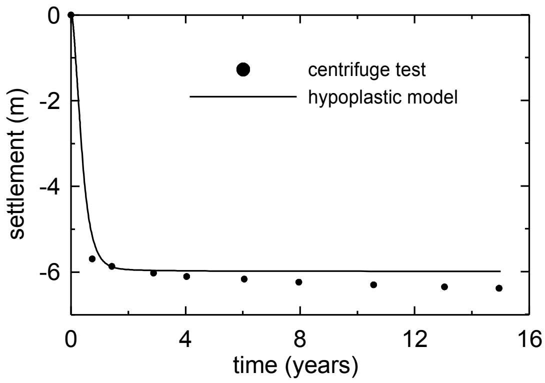

Fig. 4 Comparison of Self-Weight Consolidation of Double Porosity Clay in Centrifuge with Numerical Model.

DISCUSSION

The numerical modelling showed a significantly higher settlement after the construction of both the embankments when compared to the field data (dashed lines in Fig 5a). The calculated settlements were 3.7 and 4.4 times higher for Embankments 1 and 2 respectively. In the case of Embankment 2, the decrease of the water level during the monitoring was simulated by the increase of the unit weight of the landfill in the top 5 metres in the interval 1.6 – 2.2 years after the embankment construction. The discrepancy in the final settlements is explained by the destructuration of the landfill in shallow depth caused by weathering effects. *In situ*, the top layer is exposed to rainfall and wetting-drying cycles. The lumps are decomposed and macrovoids are partially filled with clay, which results in a lower compressibility. Similar results were obtained, when field data were compared to the centrifuge model of the trial embankment (Najser et al.

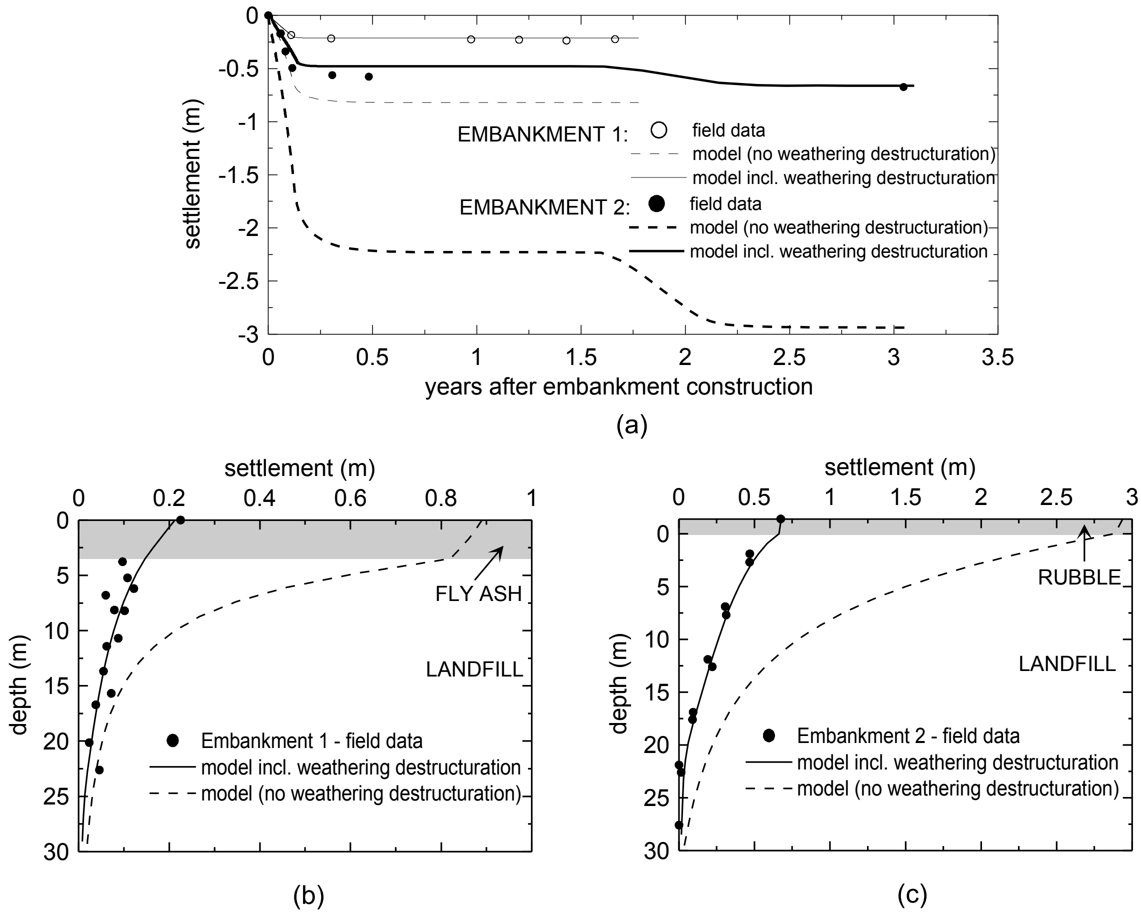

Fig. 5 Comparison of Settlements under both Embankments - (a); Final Settlements under Central Axis of Embankment 1 - (b) and Embankment 2 - (c).

2010b). The structure degradation in shallow depth due to weathering (termed as “weathering destructuration” in the following text) was simulated by an inverse analysis of the settlement data (hydrostatic levelling profiles, depth refrence points) from *in situ* monitoring. The depth reference points were installed in two boreholes under each embankment, which caused some scatter in the measured settlement (Figs. 5b and 5c).

Laboratory testing of double porosity oedometer specimens with different degree of structure degradation (Najser et al. 2009, 2010b) revealed that the degree of destructuration can be described by a continuous change in the void ratio, sensitivity and model parameter κ^*, which is influencing the initial slope of the compression curves. Weathering destructuration was simulated by reduction of e, s and κ^* after the self-weight consolidation of the landfill (before the application of fly ash/rubble layer), to reach the same settlement as measured *in situ* (full lines in Fig. 5). The change of the parameters e, s and κ^* during the modelling of weathering destructuration was described in detail by Najser et al. (2010a). Figures 5b and 5c show that most difference between the original predictions and

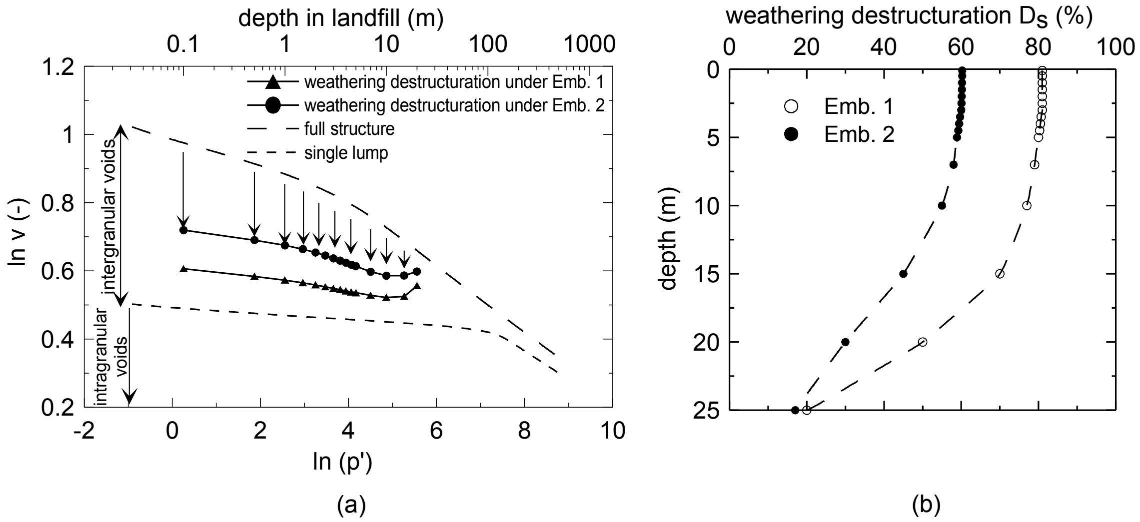

Fig. 6: (a) - Reduction of Void Ratio with Depth under both Embankments relatively to K_0 Compression of Models with and without Intergranular Porosity; (b) – Weathering Destructuration under both Embankments.

the predicitons, which include weathering destructuration took place in top 10 meters of the landfill.

The magnitude of weathering destructuration was assesed from the numerical predictions of self-weight consolidation of the structured soil before degradation and soil without double porosity structure. The model of clay without double porosity structure was calibrated from oedometer compression test of claystone, representing overconsolidated material of the lump with no intergranular porosity. Compressibilities of fully structured model and model without double porosity structure are presented in Fig. 6a. The upper dashed line represents the model with no reduction of the structure (it corresponds to dashed lines in Fig. 5). Void ratios after weathering destructuration of the landfill under both embankments are presented by full lines.

The percentage of weathering degradation with depth (Fig. 6b) was calculated from void ratios of the structured, partially destructured and intact clay presented in Fig. 6a according to equation (1) (e_{s100} refers to the void ratio of fully structured model and e_{s0} refers to the void ratio of the model without double porosity structure at the corresponding depth).

$$D_S = \frac{e_{s100} - e}{e_{s100} - e_{s0}} \qquad (1)$$

The model of the landfill was calibrated using laboratory data that characterize a chosen typical landfill with scaled down grading. The difference in the two model profiles (Fig. 6b) therefore demonstrates the horizontal variability of the landfill structure and intergranular porosity. It can vary due to the diferent shapes of clay lumps, diferent lump size distributions or segregation during the filling. A higher initial intergranular porosity results in a higher overall void ratio and higher compressibility of the landfill, even when interlump voids become completely filled with clay: the lumps remain overconsolidated and less compressible compared to clay in macrovoids.

CONCLUSIONS

A hypoplastic model for clays with meta-stable structure was used for modelling a double porosity clay landfill. The modelling of self-weight consolidation of the landfill agreed with the result of centrifuge test and demonstrated good performance of the model.

The numerical model yielded bigger settlement after embankment surcharge compared to the field data. The effect of partially filled interlump voids due to weathering in top landfill layer *in situ* was considered and the consequent reduction of void ratio, sensitivity and parameter κ^* in a vertical profile of landfill was specified. Comparison of void ratio profiles in modelling two neighbouring trial embankments demonstrated heterogeneous behaviour of the landfills.

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