

REVIEW

of Jan Najser's Ph.D. Thesis "Modelling of lumpy clay fills" submitted to Charles University in Prague, Faculty of Science, Institute of Hydrogeology, Engineering Geology and Applied Geophysics

A significant geotechnical problem, mechanical and hydraulic behaviour of a double porosity landfill material is investigated in the thesis. The landfill material is a by-product of open pit coal mining in NW Bohemia. The fill material consists of large to fine irregularly shaped clay to claystone lumps with intragranular pores and intergranular voids and forms large spoils heaps inside and outside the mines. The structure of lumpy clay fills and hence their compressibility and strength depend on a number of factors (OCR of lumps, grain size distribution, porosity, degree of saturation and loading of the fill, etc.) and changes considerably with time. Accordingly, prediction of stability, compressibility and bearing capacity of lumpy clay fills belongs to difficult, challenging problems of geotechnical design in this area.

The behaviour and structural changes of lumpy clay fill are studied in the thesis in a complex way using different methods: field measurements, centrifuge modelling, laboratory testing and numerical analysis.

The thesis consists of eight chapters and its length is $154+19 = 173$ pages including Abstract, Lists of Figures, Lists of Tables, Lists of symbols, 130 Figures, 15 Tables and 88 References. The contents of chapters are as follows:

- **Chapter 1** Introduction: motivation, aims and scope of the work
- **Chapter 2** Behaviour of double porosity soils: main features, strength and deformability of lumpy clay fills dredged from the sea and landfills of open pit mines
- **Chapter 3** Landfills in North-Western Bohemia: geological conditions, fresh and old landfills, ground improvement
- **Chapter 4** Trial embankments: landfill location, GWL fluctuation, embankment construction, instrumentation, monitoring results
- **Chapter 5** Preliminary tests in mini-centrifuge: description, soil preparation, test procedure, parametric studies, test results
- **Chapter 6** Modelling in geotechnical centrifuge: description, model preparation and instrumentation, embankment construction techniques, tests 2Da and 2Dc, self-weight consolidation, modelling of Embankment 2, comparison of settlements in situ and in centrifuge
- **Chapter 7** Numerical modelling: constitutive model description and parameter derivation, numerical modelling of mini-centrifuge tests, lump segregation, centrifuge tests 2Da and 2Dc and trial embankments, landfill consolidation, settlements due to embankment surcharge, comparison of modelling and monitoring results, weathering effects, inverse analysis of the field measurements
- **Chapter 8** Conclusions and outlook

The thesis is well structured and very well written. It is valid for both the contents and form. Up-to-date experimental and numerical methods are used for simulation understanding and interpretation of field measurement results performed on trial embankments. This is a proper way for investigating and understanding the complex mechanical and hydraulic behaviour of the double porosity materials forming the embankments.

The numerous centrifuge and numerical tests are described in clear and concise way and the results are thoroughly analysed, graphically represented and evaluated. It should be

appreciated that summaries of chapters are given and the contents of the next section outlined. This makes the orientation in the text easier.

The research resulted in a number of meaningful statements and findings, which can be grouped as follows.

Based on *references*, the following basic properties of double porosity materials are summarized in Chapters 2 and 3:

- Different mechanisms of structural changes described by Fedá: cracking / ductile deformation / densification / contact bonding
- Collapse due to saturation and wetting
- Effect of grain size and close of interlump macrovoids on deformability and hydraulic conductivity of the fill
- Decrease of friction angle with increasing vertical effective stress
- Transition of the fill from granular to cohesive behaviour with time
- Semi-logarithmic compression of the fill with fully disturbed structure is linear like for reconstituted soils

The analysis of the *field records* in Chapter 4 resulted in the following findings:

- Rapid settlements of landfills due to embankment surcharges followed by primary and secondary consolidation:
 - Embankment 1 (6 m high, crest width 4.5 m): up to 355 mm (net value 270 mm) in 6 years, gradually flooded landfill, active depth up to 20 m
 - Embankment 2 (7.5 m high, crest width 20 m): up to 674 (580) mm in 3 years, landfill flooded prior to embankment filling, active depth up to 25 m

Chapters 5 and 6 describing the *centrifuge tests* show how the author made use of advanced knowledge of European leading institutions in this field. This involves model preparation, test procedures and before all the measuring techniques applied. The main advantage of centrifuge modelling in geotechnical engineering is the possibility of simulating self-weight loading of earth structures in well-defined laboratory conditions and in scaling down duration of primary consolidation of geomaterials. The latter is not valid of course for secondary consolidation and creep.

The objective of mini-centrifuge tests was proper preparation and planning the final models of the landfills and embankments to be carried out on geotechnical centrifuge. The limitations and errors introduced by centrifuge modelling were studied and tested on mini-centrifuge. The main problem was the necessity to stop the mini-centrifuge at each measurement resulting in unloading of the model.

Nevertheless, using grain size distribution curves from the literature, different models of lumpy clay fill with scaled down lumps were prepared and tested with meaningful qualitative results:

- Both the initial settlement rate and the settlement due to self-weight consolidation are larger for the lumpy fill without fines.
- Shape of settlement curves very similar to that of in situ settlement curves was obtained.
- Filling into water is not advisable for landfill placement. Dry filling followed by fast saturation is recommended
- Oedometer tests on model material showed two different deformation processes of double porosity soil: rearrangement of clay lumps, close of macro-voids and low

elastic recovery at low stresses and a behaviour similar to that of reconstituted soil with higher elastic recovery at high stresses.

The main problem of modelling in geotechnical centrifuge with a drum diameter of 2.2 m and maximum acceleration of 440 g was embankment construction without stopping the centrifuge, i.e. without swelling of the landfill creating the subsoil of the embankment. Two models were set up:

- Model 2Da with an embankment made from sand constructed after stopping the centrifuge; settlement measurements by laser scanner on the surface.
- Model 2Dc with an embankment made from lead balls constructed in-flight without stopping the centrifuge; settlement measurements in depth using a system of straws.

Along with the settlements and pore pressures were measured during the tests. The results of self-weight consolidation tests, which could not be compared with monitoring results, showed high compressibility of the modelled landfill (up to 22 %), but quite realistic distribution of settlements with depth. The pore pressure measurements at different depth indicate higher hydraulic conductivity of the upper part of the model (open preferential paths) than that of the deeper part (closed macro voids).

Careful modelling of Embankment 2 in geotechnical centrifuge resulted in the following findings:

- The direct comparison of the pore pressures measured in situ and in centrifuge shows higher excess pore pressures induced by the embankment surcharge in situ (100 to 200 kPa) than in the model (50 kPa). This indicates lower hydraulic conductivity of the in situ landfill than the modelled fill. On the other hand, the rate of in situ consolidation is faster than registered by the model.
- The comparison of centrifuge and field consolidation curve show very similar shape, but the net field settlements are lower (about 0.5 m) than those measured in the centrifuge (about 1.2 m). This indicates different intergranular porosities in situ and in the centrifuge model, which is explained in the work by structure degradation of the fill due to the following reasons: surface weathering of the landfill / ground water conditions / preloading by a rubble stone layer.

All centrifuge tests (mini-centrifuge tests, tests 2Da and 2Dc, trial embankments) and a number of related phenomena (unloading-reloading cycles, lump segregation effect, hydraulic conductivity, landfill height, structure degradation due to weathering, etc.) were modelled and evaluated using *numerical models* and parametric studies described in Chapter 7. Hypoplastic constitutive model for clays with structure degradation law was used for simulating the lumpy clay landfill. This model introduces an additional state variable for sensitivity, which is defined as the ratio of the size of structured clay yield locus to the corresponding size of the reconstituted clay yield locus.

The basic hypoplastic model was calibrated using laboratory tests on reconstituted clay. The additional parameters for structural changes were derived from mini-centrifuge oedometer tests on the double porosity clay specimens with scaled-down lumps.

The basic results of numerical modelling can be summarized as follows:

- The calibration resulted in different initial parameters (void ratio and sensitivity) for each mini-centrifuge oedometer test.
- Numerical models of mini-centrifuge tests produced larger settlements (4.74 m and 9.8 m) than those measured in the centrifuge (3.8 m; 8.4 m). Analysis of unloading-reloading reduced this difference.

- Experiments with lump segregation and their numerical modelling provided clear results and explained well the reasons for differential settlements registered by both the measuring profiles in situ and in centrifuge.
- Good agreement of self-weight consolidation of the landfill measured by 2Da and 2Dc models in centrifuge and computed by the corresponding numerical models is presented.
- Unfortunately, it is not valid for the landfill settlement induced by the embankment surcharge: 2 m by the numerical model, 1.2 m in centrifuge and 0.5 m in situ. Parametric study of the stress dependency of hydraulic conductivity of the fill did not help to solve the problem.
- Even higher difference between measuring and modelling was obtained when Embankment 1 and Embankment 2 were modelled using hypoplastic model for structured clays with void ratio and sensitivity obtained from the centrifuge model. The calculated settlements induced by embankment construction were 3.7 and 4.4 times higher than those measured in situ.
- Inverse analysis of the in situ settlement data and introduction of degradation of the landfill structure into the numerical model helped to solve the problem. The void ratio was reduced according to the field records and the corresponding sensitivity and stiffness parameters calculated. Degradation of the landfill structure higher at the surface and varying with the depth resulted in good agreement of measuring and modelling. The degradation of the landfill structure is explained by weathering of the top 10 metres of the landfill.

The presented overview of the main results of the thesis shows once again the large extent of the research carried out by the author and the thorough analysis of almost all aspects related to the subject. Nevertheless, regarding the complexity of the problem some comments should be added.

1. In the literature review, the works dealing with particulate materials in the framework of discontinuum mechanics are missing. The basic feature of the double porosity materials is their discrete nature and the character of particles and their contacts determine their structure. This can be well simulated by distinct element method, namely by particle flow codes (PFC). Micromechanical modelling of a dump material has been performed at the department, where the thesis is submitted.
2. The carefully performed centrifuge tests confirmed once again the reviewer's experience that rather qualitative than quantitative conclusion can be made on the basis of centrifuge modelling. The limitations regarding the simulation of construction sequence, keeping the maximum g-level, watering and measuring of the model during loading make difficult to get realistic results corresponding the field performance of geotechnical structures.
3. There are two key features of the double porosity soil behaviour, which are only partly discussed and not explicitly simulated by the tests presented in the thesis:
 - a. The first one is grain (lump) breakage induced by loading. The sensitivity of the scaled down lumps to break in centrifuge might have been influenced by scale effect. No lump size distribution after tests are presented in the thesis.
 - b. The second feature is structural collapse due to wetting at the first saturation of the fill. This collapse depends on porosity of the fill, degree of saturation of

lumps and on the vertical effective stress. The key moment is the first flooding of the fill under loading.

4. Such a collapse surely happened to the landfills prior to embankments construction and this might be one of the reasons for densification of landfills resulting in relatively high stiffness. Some additional structural changes and degradation due to weathering might have been occurred in the upper parts of the landfills as well, but the largest structural collapse likely happened due to first saturation induced by ground water level increase in the early stage of existence of landfills.
5. Lack of these effects in the centrifuge oedometer tests could explain why the numerical model produced 4 times larger settlements when the structural parameters of the constitutive model were derived from these tests. Inverse analysis of these parameters from field measurements results accounted for these effects and therefore solved the problem with acceptable results.
6. Description of some details of numerical modelling (brief description of the code and the coupled analysis, reasons for no convergence of some numerical solutions, reasons for introducing truss elements with high stiffness, hydraulic boundary conditions, etc.) is missing.
7. The recommended method of landfill placement depends on the type of structure formed by the landfill and the conditions at present. Dry placement followed by saturation can be recommended for subsoil without slope stability problems. Otherwise protection of landfill from water infiltration and application of drainage systems are necessary.

Regardless to these comments, the above listed outstanding results of the experimental and numerical studies performed by the author demonstrate that the thesis is an excellent research work of high academic standard, which is worthy of being publicly defended. The thesis surely fulfills the requirements for the degree of Doctor of Philosophy in Geotechnical Engineering.

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June 15, 2010

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