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Transitions in structure of clay fills due to suction oscillations

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Abstract

In North-western Bohemia the excavated overburden from open-cast coal mines is end-dumped in fills. Clay-type soil prevails among the filled soils. As a consequence of the character and state of the soil, together with the mining and dumping technology, the clay fill comprises a typical lumpy structure. Large and open macrovoids between the single lumps are a characteristic feature of the clay fills. The filled overburden forms spoil heaps under high angles of repose (as high as 40º) which is governed by size and shape of the lumps. However these slopes cannot be considered for design of clay fill final slopes. The lumpy clay fill structure is metastable. Structure transitions influencing the mechanical behaviour and thus slope inclination of the heaps are presented in this contribution. Three main agents are responsible for the transitions of the lumpy structure: Plastic straining of relatively weak lumps as a consequence of overburden load; collapse on wetting of the open metastable structure mainly in the early stages after landfilling; and oscillations of matric suction. Long-term monitoring of matric suction in years 2004 – 2008 at depths up to 2 metres in the low-gradient slope of the reclaimed clay fill in the Bílina mine show clear seasonal suction oscillations.

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Keywords: Clay fill; Lumpy soil; Structure degradation; Matric suction oscillations,

1. Introduction

Fine-grained overburden materials removed during open-cast coal mining form clay fills with an intricate mechanical behavior. This situation is described with reference to the region of North-western Bohemia (Czech

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Republic), where the brown coal seams are overlain by sedimentary layers varying in thickness between 80 m and 200 m. The clay fills formed by the displaced and disintegrated clay can reach heights greater than 100 m. An area of about 100 km^2 has been affected by the clay fills in North-western Bohemia. The deposition process takes place without any artificial compaction. Consequently, the clay fills have a loose structure, particularly in their upper part (i.e. in the range of small overburden pressures). Clayey soils of the overburden often form lumps, resulting in dumped soil with double porosity. With increasing depth, the compression induced by the own weight of the soils squeezes the individual lumps, destroys them and creates a new compacted clayey material without macrovoids. Even close to the surface, the structure of the clay fill varies in time because weather influenced suction cycles destroy of the clay lumps.

The excavated overburden is filled on heaps under the angle of repose, which is initially high, depending on the state and the grain size of the filled material. Angles of repose of about 40° prevail. However these high angles of repose are relevant for the short term stability of single heaps only and cannot be considered for the design of final slopes. Since the structure and therefore the mechanical properties of the filled material vary in space and time, the final slopes should be much gentler. For example, Blight[1] recommends that the final slopes should be flatter than a slope with an acceptable factor of safety, and should not exceed an inclination of 15°. A typical inclination of the final slopes of fills in North-western Bohemia is 6°[2]. Dykast et al.[3] reported some huge instabilities even in slopes with a general inclination of approximately 5° and 100 m in height. The landslides were attributed to the degradation process of the originally lumpy clay.

1.1. Double porosity structure

A metastable structure of clay fills with lumps of variable size (typically up to 0.5 m) is formed as a consequence of excavation technology, soil transport and deposition. The total porosity of such material is due to the primary voids of the clayey lumps (intragranular porosity, typically 40% according to Feda[4]) and to the voids between the lumps (intergranular porosity). The total porosity of such material n_{tot}, which reaches up to 70%, is given by

$$n_{tot} = n_i(1 - n_e) + n_e \quad (1)$$

where n_e and n_i are intergranular and intragranular porosities. Soon after emplacement the clay fill looks like a coarse-grained material (Fig. 1 - left). Due to this structure there is no (or negligible) suction within the intervoids and some suction within the intravoids in the lumps, where the negative pore water pressures were induced first by water-level sinking and subsequently by unloading due to excavation. Further suction within the lumps is related to the weather dependent moisture changes. This structure however does not persist for a long time. Water enters the

Fig. 1 Lumpy structure after landfilling (left); partly degraded structure 6 months after landfilling (right)

clay fill material easily during the early stages after landfilling. The intergranular macrovoids form preferential paths for infiltration of surface water, while intragranular voids (natural porosity) inside the lumps do not contribute to water flow. Such an open structure forming interconnected flow channels results in high permeability to both water and air until the structured soil degrades (Fig. 1 - right). Transitions of clay fill structure influencing the mechanical behaviour of this material and main processes leading to structure degradation are presented and discussed in this contribution. Standard laboratory tests on specimens with downscaled lump sizes up to 5 mm are presented. Size effects are discussed closer by Herbstová and Herle[8].

2. Characterization of studied soils

Soils ranging between silty clays and sandy silts mostly overlie the brown coal seam, which is 25-40 m thick. Lacustrine and deltaic sediments were deposited in Miocene in the North Bohemian brown coal basin. The Bílina delta, characterized by a high grain-size segregation of deltaic deposits, gradually passes into Libkovice Series[5]. The sediments of the Libkovice Series are the thickest and can be characterized as monotonic lacustrine silty clays. In the deepest parts of the North Bohemian brown coal Basin the Libkovice series reach the thickness of about 300 m[6]. After the geologic uplift, an unknown extent of erosion took place in the basin. According to the reconstruction of the overlying complex in the Most basin by Hurník[7], the original thickness of the sedimentary layers is estimated to be as much as 550 m. The subsequent erosion could range between 70 and 300 m. The original soil forming the lumps can be classified as an overconsolidated clay of high plasticity with the natural water contents of about 30-34%. Its index properties are summarized in Table 1. Disturbed samples in the form of lumps and undisturbed samples were collected for this study.

Table 1. Index properties

Plastic limit w_P(%)	Liquid Limit w_L (%)	Plasticity Index I_P (%)	Activity A (-)	Particle density ρ_d (g/cm^3)
36	94	58	1.6	2.675

3. Properties of clay lumps

3.1. Uniaxial strength

The strength of clayey lumps forming the fills is influenced by matric suction, overconsolidation and possible diagenetic processes (see also Herbstová and Herle[8]). Uniaxial compressive strength was estimated from tests on irregular clayey lumps ranging in diameter between 15 and 30 mm and having a height/diameter ratio of approximately two. The values of σ_c between 0.53 and 1.06 MPa are below the typical uniaxial compressive strengths of weak rocks.

3.2. Matric suction

The excavated overburden is deposited into fills in a “dry” way at its natural water content. Therefore, macrovoids between the lumps are typically air-dry while the intragranular voids in the lumps contain some water. The natural water content of lumps reaches about 30 – 34%. The degree of saturation was determined from the measured volume, mass and water content of several clay lumps. The volume of lumps was measured by weighing under water. The resulting S_r of the lumps ranged between 0.98-1.00.

Matric suction was determined using the filter paper method (according to ASTM[9]) on lumps sampled about 4 – 5 months after landfilling. The filled material was a lumpy soil with blocks up to 0.3 m and a finer matrix. The matric suction was determined on the lumps of about 150 - 200 mm size. Each lump was halved by a wire saw and the filter paper Whatmann nr. 42 was placed between two protective filter papers inside the halved sample. The two halves of the sample, with the sandwiched filter papers in between, were tightly put together, properly wrapped into a protective plastic film and placed into an air-tight container. The equilibrium time of 14 days was used to ensure a steady state between the moisture of the filter paper and matric suction of the lump. The results are summarized in Table 2. The measured matric suction of the lumps varies between 2440 kPa and 1267 kPa accompanied by a moisture content variation of 1.6% (see Table 2). This could be attributed to the overconsolidation of the lumps and their small void ratio.

Table 2. Water content of the lumps and matric suction, measured by filter paper method.

Moisture of the lump w(%)	Matric suction according to ASTM s (kPa)
28.2	2440
29.5	1470
29.8	1267
29.3	1776

3.3. Overconsolidation

Clayey lumps of the clay fills are overconsolidated not only as a result of their exploitation by mining from large depths, but also due to a considerable erosion of the overburden in the geological history (see Hurník[7]). The amount of the erosion was estimated in the laboratory by comparing the void ratio of sampled lumps with results of one-dimensional compression tests on specimens prepared from slurries0. A thickness of eroded layer between 237 and 349 m was estimated which is in a good agreement with Hurník[7], who reported eroded thickness between 70 to 300 m.

3.4. Diagenetic bonding

The ageing of sedimentary soils results in diagenetic processes, mentioned e.g. by Hurník[7], which add a strength component to the lumpy soil. This component is independent of water content and resists water saturation. Naturally wet lumps submerged by water remain intact with time, thus confirming a kind of diagenetic strengthening (see Sect. 5.1).

4. Matric suction in reclaimed clay fills

4.1. Monitoring of matric suction

Classic jet-fill tensiometers were used for the long-term monitoring of matric suction at the clay fill of Bílina mine. The maximum suction measured by standard tensiometers is 90 kPa (see e.g. Fredlund and Rahardjo[10]). Positive pore water pressures can be also recorded by the tensiometer analogously to piezometer. Tensiometers with lengths between 0.5, 1 and 2 metres were used. The in-situ suction measurements started in May 2004 and lasted 4.5 years till the end of 2008. Readings were taken manually in 14 days to 3 weeks intervals. Tensiometers were installed in a gentle slope in three groups: locations L01 and L02 in Fig. 2 were placed in the slope, while location L03 was placed below the slope. The seasonally dependent cyclic suction oscillations were recorded. The maximal measured suctions reached about 90 kPa in late autumn, which is the limit for this type of gauges due to cavitation. Actual suctions in the field could be higher than 90 kPa in this period. In late winter and spring the suction dropped to values close to zero even in the deeper gauges. The two uphill groups (L01 and L02) showed consistently higher suctions even in winter period (Fig. 2- top). On the contrary, just the shallow tensiometers (Fig. 2- bottom, gauges T051, T113, T114) from the bottom group (L03) exhibited moderate and high suctions in summer and autumn (95 kPa at maximum), while during the wet winter period suction vanished. The tensiometers installed at the depth of 1.9 m (Fig. 2– bottom, gauges T223, T224, T227) showed permanent lower suctions. The groundwater level was in the depth of 17 metres and does not influence the suction measurements. The higher suctions in uphill groups during dry periods may be explained by the surface and shallow subsurface runoff.

4.2. Hydraulic characteristics

Hydraulic conductivity strongly depends on the soil structure and its interconnected voids. Hydraulic conductivity of clay fills varies as the structure changes. As the originally open and interconnected intergranular voids close, the hydraulic conductivity decreases by several orders of magnitude. Tests to simulate the changes in hydraulic conductivity in the saturated state at increasing stress levels in the laboratory conditions have been performed on the lumpy specimens with reduced lump size up to 5 mm. Specimens were prepared by a gentle compaction of the lumpy soil at its natural water content, saturated using the back pressure of about 5 kPa and than consolidated to different isotropic effective stresses in the triaxial cell. At each effective stress a constant head permeability test was performed. The hydraulic conductivity was strongly stress-dependent (see Fig. 3-left). It

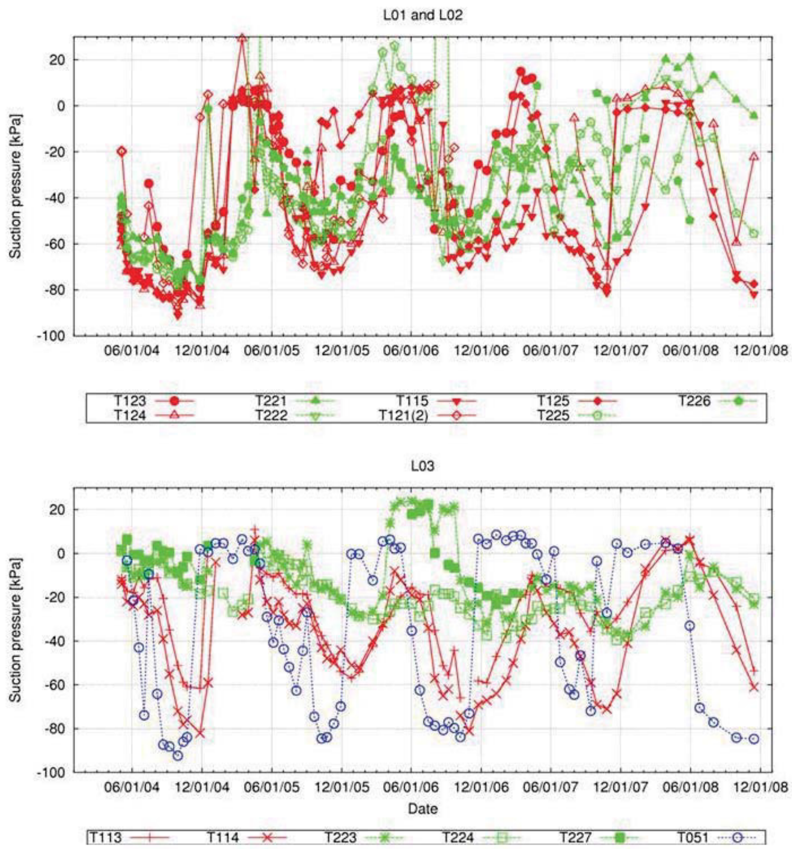

Fig. 2. Field measurements of matric suction; Outputs from 0.5 m (blue), 1 m (red) and 2 m (green) long tensiometers

dropped from about 4* 10^{-6} m.s^{-1} at the isotropic effective stress of 30 kPa, which corresponds to the hydraulic conductivity of sands, to 2 * 10^{-11} m.s^{-1} for the specimen consolidated at 500 kPa, which corresponds to hydraulic conductivity of clays used in landfill mineral linings. The decrease in hydraulic conductivity of 5 orders of magnitude was caused by the progressive filling of intergranular macrovoids. Consolidation of the specimen to a

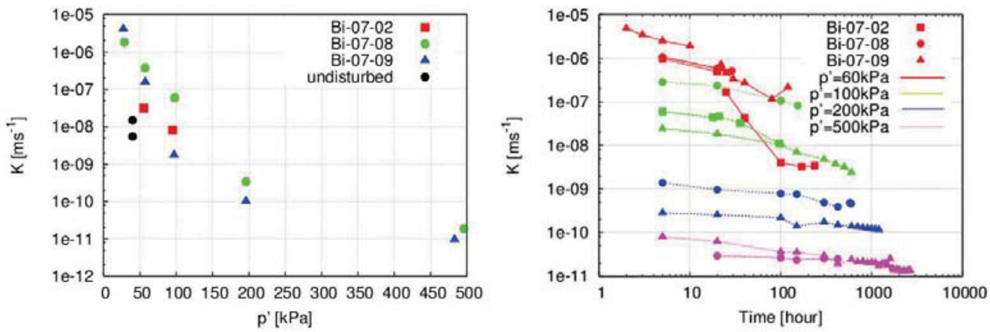

Fig. 3. Dependence of saturated hydraulic conductivity on mean stress (left); and time for different stresses (right)

given effective stress caused deformation of the softened clayey lumps and lump contacts, which progressively filled the intergranular voids. At higher stresses, the low intragranular porosity of the lumps starts to contribute to flow paths more significantly due to progressive filling of intergranular macrovoids.

Hydraulic conductivity of the lumpy material is furthermore influenced by the duration of the loading stage. Hydraulic conductivity of a specimen, which was left for about 1 month at the effective stress of 60 kPa, dropped from $1.7*10^{-6}$ $m.s^{-1}$ to $4.3*10^{-9}$ $m.s^{-1}$ (see Fig. 3 - right). A creep of contacts of lumps (see Herbstová and Herle[8]) can explain this effect. Furthermore, the decrease of hydraulic conductivity was observed at increasing stresses (see Fig. 3- right).

Water retention curves (WRC) were determined in the standard pressure plate apparatus on lumpy specimens compacted to the density of $\rho_d = 1.25$ $g.cm^{-3}$ at the natural water content of w = 34% (BiCom in Fig. 4) and on undisturbed specimens (BiUn in Fig. 4). The highest applied matric suction was 1500 kPa. Just the drying path of WRC was measured and therefore the hysteresis was not taken into account. A freeware program RETC[11,12] was used to estimate model parameters. van Genuchten's retention model[13] was used for representing the WRC of both lumpy and undisturbed specimens (Fig. 4).

4.3. Inverse analysis of matric suction using the dual permeability approach

Water flow in dual-permeability models is described using separate flow and transport equations for the fracture (macropores) and for the matrix (micropores). Two domains with different hydraulic and transport properties are assumed for the system of the structured porous media; both domains can hydraulically communicate with each other. The S1_D Dual program (Vogel et al.[14]) was used to model the matric suction. The model considers variably

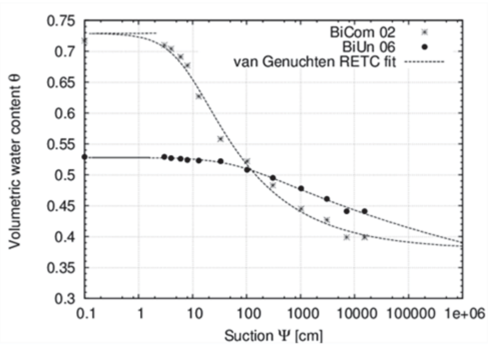

Fig. 4. Water retention curves

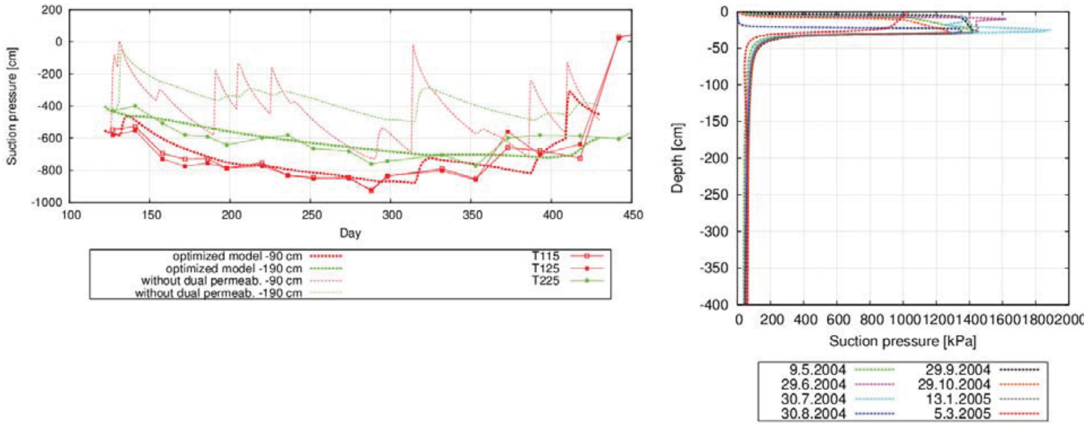

Fig. 5 Optimizing simulations to the monitored data (left); suction profiles for different times of the simulated period (right)

saturated pore space and dual permeability. Matrix domain w_m and the preferential flow (flow through fissures) domain w_f are prescribed per unit volume of the bulk soil with $w_m + w_f = 1$.The total water content is thus the weighted sum of water content in preferential flow and matrix domains:

$$\theta = w_f \theta_f + w_m \theta_m \quad (2)$$

A pair of Richard equations of flow for both preferential flow and matrix domains is solved in every iteration step (details in Císlerová et al[15]). Hydraulic conductivities at low effective stresses and the soil water retention curves, determined on the undisturbed and lumpy specimens, respectively, were used for hydraulic characteristics of matrix and preferential flow domains. Hydraulic characteristics of the lumpy specimens with a reduced lump size can only roughly characterize the preferential flow domain. Both intragranular voids in lumps, representing the matrix, and intergranular macrovoids between them, representing the preferential flow domain, are present in lumpy specimens. However intragranular voids start to contribute to water flow more significantly only at higher effective stresses (see Sect. 4.2). Water flow in shallow depths was modeled. Data from distant hydrometeorological stations were used for the upper boundary conditions. The main outputs from the simulations are:

- The vertical profiles of matric suction are obtained (Fig. 5 - left) using the inverse analysis and fitting to the monitored data (Fig. 5 - right).
- Different volumetric fractions of the matric and preferential flow domains in different depths result in a better match with the measured data.
- High matric suction reaching 1.8 MPa in late summer and suction oscillations are obtained in the shallow depths (Fig. 5 - left).

The simulated high matric suctions in the shallow depths and frequent suction oscillations, even in the reclaimed clay fills, emphasize the importance of the wetting-drying cycles on the degradation of the structure of clay fills. However in freshly filled clay fills the suction can reach higher values and the suction oscillations can be more pronounced, since the surface of the fills is exposed. The results of the presented simulations should be evaluated rather from the phenomenological point of view, particularly regarding the volumetric fractions of the matrix and the preferential flow domains. The hydraulic characteristics were determined on the lumpy soil with reduced size of lumps and small undisturbed specimens which may not necessarily reflect the characteristics of a large soil volume in situ.

5. Transitions of clay fill structure

5.1. Disintegration of a single lump induced by suction cycles

A simple test confirmed the relevance of wetting-drying cycles on the structure of a single unconfined lump. Two similarly saturated hard lumps with initial water content of 30% were selected. The two lumps were submerged in a dish with tap water under room conditions (22±2C).

The first lump (Fig. 6 - top) remained submerged for the whole testing period (approximately forty days), while the second lump (Fig. 6 - bottom) was exposed to 4 wetting-drying cycles. During a cycle the water in the dish was simply allowed to evaporate and was re-filled afterwards. Each cycle lasted approximately ten days. The first lump remained almost intact throughout the test, and a single wetting event did not affect its shape (see Fig. 6- top). On the other hand, disintegration of the second lump was already visible after two wetting-drying cycles (see Fig. 6 - bottom), and the first small cracks appeared. The ongoing disintegration during the third and fourth wetting-drying event caused the lump to separate into smaller angular platy fragments (see Fig. 6 - bottom, third and fourth picture). Owing to the fact, that the first lump (Fig. 6 - top) was fully saturated at its natural water content prior to the submersion and was not exposed to any drying surpassing its air entry value, the pore pressure gradient between the matrix fluid and water under atmospheric pressure was not sufficient to break the lump structure. Therefore, the submersion only equilibrated the two pressures and the effective stress within the lump reduced. The matric suction of similar lumps at natural water content varied between 1.2 and 2.4 MPa (see Sect. 3.2). Thus the matric suction of similar magnitude vanished during submersion, without causing any flow between the inner pores of the lump and the surrounding water.

5.2. Collapse on wetting

Collapse potential of the lumpy soil was evaluated using the technique of double oedometer tests (Tokar, 1937, in Abelev[16]). Comparing the compression lines (CL) of a specimen compressed at natural water content with the 'identical' specimen, inundated at low total vertical pressure, allows to evaluate the collapse potential at different loading steps. Lumpy soil with downscaled lumps up to 5 mm and natural water content (w_n = 34%) was used. Two sets of the tests were carried out on loose and compacted soil (Fig. 7). Severe collapse potential (according to ASTM[17]) was found for both loose and compacted lumpy specimens at low vertical stresses. This was also confirmed by standard collapse tests, by flooding the specimens at σ_v = 200 kPa (in Fig. 7 - right). Collapse potential vanishes at vertical stress of about σ_{ax} = 1500 kPa, where flooded (saturated) and natural moisture CL unite and also the slope of CL of lumpy specimen at w_n changes (Fig. 7 - left). In the region of σ_v > 1500 kPa the intergranular

Fig. 6. Lump submerged in water (top); lump exposed to 4 wetting-drying cycles (bottom)

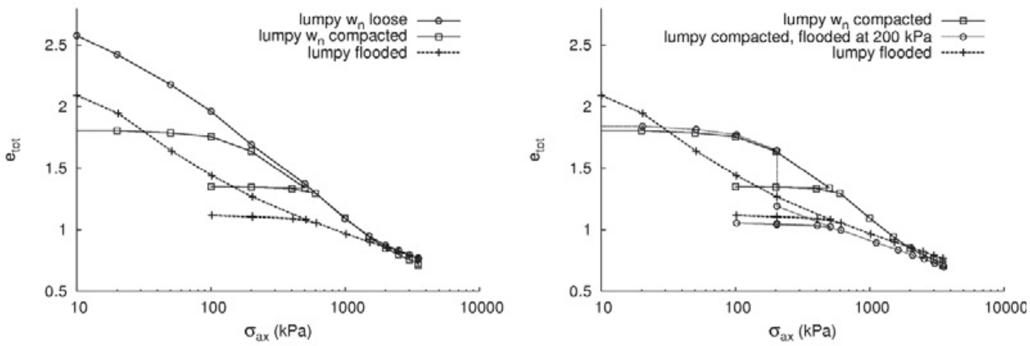

Fig. 7. Compression curves of natural loose, compacted (full lines) and flooded (dashed lines) lumpy specimens (left); compression curves of compacted, flooded and flooded at 200kPa (dotted lines) lumpy specimens (right).

porosity vanishes and the compressibility is controlled only by the intragranular voids. After the sample dismantling at the end of the test, no obvious structure was visible. The material was homogenized in both natural moisture and saturated states (details in Herbstova et al.[18]).

5.3. Compression due to overburden load

Comparing the compressibility loose and compacted lumpy specimens at natural water content and reconstituted clay (Fig. 8 - left), higher compressibility of the lumpy specimens can be observed. CLs of both reconstituted and lumpy clay come close together at the stress about 1500 kPa. Horizontal lines in Fig. 8 - left, denote the range of intragranular void ratios inside the undisturbed lumps, which intersects the CL of the lumpy clay close to the stress of about 1500 kPa. This confirms the lumpy structure with open intergranular macrovoids of the natural moisture specimens up to this threshold. The CL of flooded lumpy specimen (dot line in Fig. 8 - left) lies below the compression line of reconstituted specimen (dash and dot line in Fig. 8 - left) and once again unifies at stresses > 1500 kPa. The destruction of the macrovoids by water saturation is accompanied by squeezing of clayey mass with high water content into the macrovoids. The total porosity is given by both, a low intragranular porosity of the softened overconsolidated lumps and a high porosity of the paste, the latter being close to the one of the reconstituted soil. Therefore, the flooded specimen has a lower total porosity than the reconstituted specimen up to the mentioned threshold, where the lumpy structure vanishes.

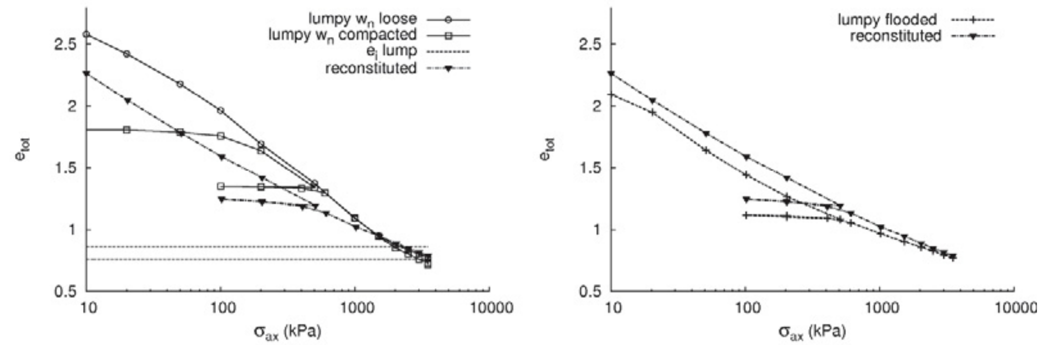

Fig. 8. Compression curves of loose and compacted lumpy specimens (at natural water content, full lines) and reconstituted soil (dashed lines, left); compression curves of lumpy flooded (dotted lines) and reconstituted specimens (right).

6. Conclusions

Structure and mechanical behavior of clay fills composed of oveconsolidated lumps vary in time and space. Originally high-angle heap slopes are not stable and are affected by structure transitions of the lumpy soil. Surface water easily enters macrovoids between the lumps and changes the originally unsaturated state of clay fills. Disintegration due to oscillations of matric suction, collapse on wetting and compression due to overburden load are the three main processes causing degradation of the originally open and metastable lumpy structure. Seasonal suction oscillations, with maximums reaching 85 to 90 kPa in late summer and autumn, were recorded by tensiometers in the moderate slope of a reclaimed clay fill. Inverse analysis of the measured matric suctions using dual-permeability concept confirms the importance of suction cycles mainly at shallow depths. A decrease in suction contributes to the destruction of the clayey lumps and to subsequent filling of the intergranular macrovoids with finer disintegrated mass. It has been shown that the lumps subjected to wetting-drying cycles disintegrate to small angular fragments, while the lumps flooded at their natural water content remained intact. Severe collapse potential was measured on both loose and compacted lumpy specimens with reduced lump size. Intergranular macrovoids of the lumpy soil at natural water content vanishes at an axial stress of 1500 kPa. Compression lines of saturated lumpy specimens lie below that of the reconstituted soil up to about 1500 kPa, and can thus have a stiffer response to loading up to this stress. The decrease in saturated hydraulic conductivity of 5 orders of magnitude was caused by this progressive filling of intergranular macrovoids. All these transitions change the originally lumpy structure gradually back to more or less homogenized and low permeable fine grained soil.

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