Constitutive Modelling of Multiporous Lumpy Soils

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Abstract. The deposition of excavated natural soils, e.g. in open pit mines or during land reclamation, produces in general lumpy soils with multimodal pore sizes. The mechanical behaviour of such soils is determined by interaction between the firm to stiff lumps and the soft to liquid soil material in the macrovoids between the lumps. The initial skeleton composed of lumps resembles a coarse grained soil. However, contrary to mineral grains, the macrograins (lumps) are not incompressible and time-independent. Due to rising overburden during the subsequent deposition of the excavated soil, a time-dependent deformation of the lumps takes place, being accompanied by a softening of the lumps' surface. The space between the lumps, originally occupied by air, becomes gradually filled with that soft material. A constitutive description of the lumpy soils should take into account all the mentioned effects. In this paper, main ideas and fundamentals for the constitutive modelling of the relevant phases of lumpy soils are outlined. With help of a homogenization method, a material model suitable for practical applications can be obtained.

1 Introduction

An excavation and a subsequent deposition of large volumes of natural soils can be encountered e.g. in open pit mining or in land reclamation. In case of open pit mining, bucket wheels disintegrate the original, often stiff soils into big lumps (Fig. 1 left). After their transport to the deposition location, the lumps are being spread in a material flow from a non-negligible height (Fig. 2 right) and thus further broken. An initial structure of the lumpy skeleton resembles a coarse grain soil (Fig. 3 left). The macroscopic voids between lumps are continuous and filled with air. One can observe steep slopes created during spreading which suggests a high friction angle of this artificial coarse grained soil.

Contrary to mineral grains, the lumpy macrograins are composed of numerous primary grains with their own (microscopic) porosity. If clay particles are

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Fig. 1. Excavation of natural soil layers.

Fig. 2. Deposition of the excavated soil.

involved, additionally pores inside the clay aggregates can be distinguished. The primary grains are held together in a lump by suction, interlocking or natural cementation. The lumps are far from being permanent due to their particulate nature. They can change their shape and volume during loading or in time. Even more pronounced is their degradation due to environmental impacts, mainly oscillations in humidity or rainfall events [1,3].

The lump degradation by weathering starts from the surface of a lump. Getting into contact with water or excessive humidity, the suction at the surface is suppressed and the surface layer becomes saturated. Effective stresses vanish and the surface layer softens. A reconstituted soil is created and gradually squeezed into the pore space whereas the volume of the stiff lump diminishes

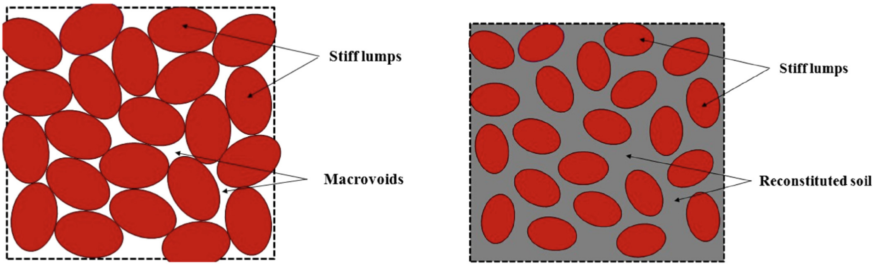

Fig. 3. Fresh (left) and weathered (right) lumpy soil [5].

(Fig. 3 right). Simultaneously, a total pressure on the lump is increasing due to overburden from a further deposition of excavated soils. A continuous transition from a granular soil to a reconstituted soil takes place in time and with depth.

A constitutive description of a lumpy landfill including the process of lumps deformation can be split into several particular models:

- granular soil composed of lumps and voids filled with air [1,5,11,16]
- fully reconstituted soil [4,6,9,13]
- mixture of lumps and reconstituted soil without consolidation [8,10,12]
- mixture of lumps and reconstituted soil considering overconsolidation of the lumps [7,14]
- mixture of lumps and reconstituted soil including coupled consolidation of both components [15]

A selection or combination of these models can be used for predictions of stability and deformation behaviour of landfills composed of double porosity soils.

2 Lumpy Soil as a Granular Soil

Fresh lumps are created by the disintegration of the excavated soil during its transport and deposition. Considering the lumps as soil grains, the resulting soil could be characterised as gravel with cobbles and boulders. Nevertheless, the lumpy grains are soft, having the uniaxial strength usually not higher than 1 MPa [1]. In order to reduce the grain size of the natural lumps for laboratory investigations, the original soil was cut into small pieces representing the downscaled lumps (Fig. 4).

The soft nature of the grains produces some untypical phenomena like densification of the soil during shearing, in spite of a high initial relative density [16]. Although the volume decreases during shearing, the shear strength is higher than in the reconstituted (normally consolidated) state. After normalization with Hvorslev's equivalent pressure, the state boundary surface of a lumpy soil can be defined (Fig. 5).

With increasing stress level, the preconsolidation pressure of the original soil material (before being excavated) is being approached. Even without any

Fig. 4. Downscaled natural lumpy soil [16].

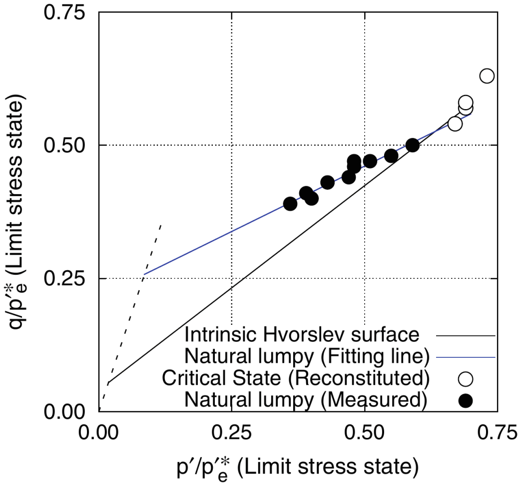

Fig. 5. Limit stress state of a downscaled natural lumpy soil [16].

degradation (weathering) effects, the lumps are excessively distorted and fill the macrovoids between each other. Although the compression behaviour may resemble a natural soil with a metastable structure, significant differences can be found when interpreting the data with respect to the intrinsic compression line [11], see Fig. 6.

At higher pressures, the mechanical response of a lumpy soil tends to the normally consolidated behaviour of the constituents within the lumps [1]. This process results in a pronounced reduction of the overall permeability and thus an increase in the consolidation time [5].

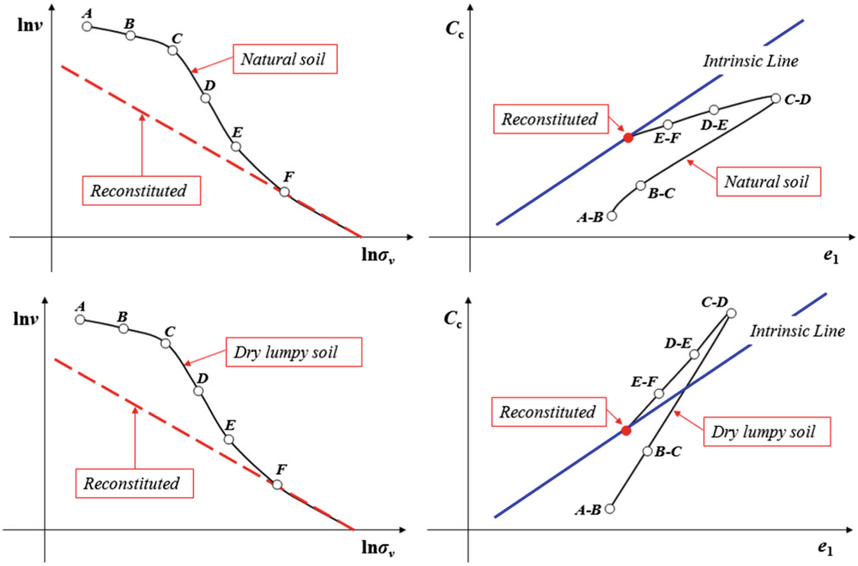

Fig. 6. Difference in the structure transition between the natural and dry lumpy soil [11].

3 Mixtures of Reconstituted Soils

Oscillations in atmospheric conditions are responsible for weathering and subsequent disintegration of the lumps. Asymptotically, after sufficient time, a reconstituted soil is created. Nevertheless, in cases of long transportation of the excavated material on conveyor belts the lumps may become fully disintegrated and reconstituted prior to their deposition. Under such circumstances, various soils in the reconstituted state may be mixed together during the transport.

The properties of mixtures of fully saturated reconstituted soils cannot be obtained by a simple interpolation between the constituents. The remolded shear strength can be estimated from the consistency limits and the actual water content of the constituents [9]. An evolution of the shear strength in time within artificial deposits (landfills) requires the knowledge of a statistically probable composition of the soil mixtures and their states [2]. Cone penetration testing may be useful for the determination of the soil composition and state of heterogeneous mixtures in the field [17].

4 Lumpy Soil Without Consolidation

When the voids between the stiff lumps are filled with a reconstituted material as a consequence of the lumps weathering, two constitutive phases—lumps and reconstituted soil—must be distinguished. The following four partial volumes should be taken into account:

1. solid material of the lumps
2. solid material of the reconstituted soil
3. voids between the lumps
4. voids in the reconstituted soil

It can be assumed that the behaviour of each phase is controlled by its average stresses and strains. The overall stresses and strains are related to those of the constituents through their volume fractions. The overall stiffness can be expressed as a function of the stiffnesses of the constituents using a stress concentration ratio.

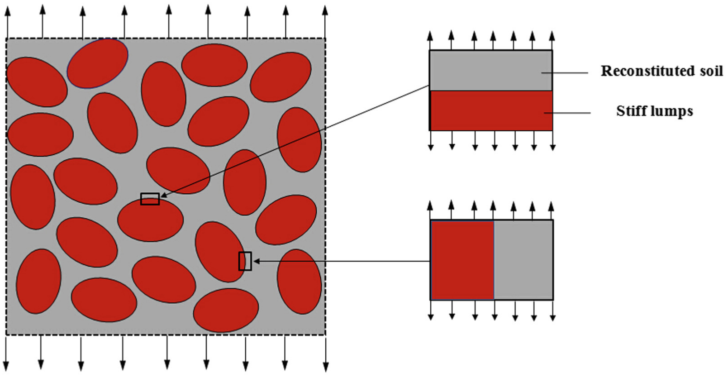

Fig. 7. Limit cases of the phase interaction for a two-phase composite soil [8].

Two limit cases can be defined for the contact between the lumps and the reconstituted soil at the mesoscale, see Fig. 7. These can be described as a parallel and a series configuration, respectively, of the two phases. Denoting K_r the stiffness of the reconstituted soil and K_l the stiffness of the lumps, the overall stiffness can be calculated as

$$K_p = n_e K_r + (1 - n_e) K_l \tag{1}$$

in the parallel case and as

$$\frac{1}{K_s} = \frac{n_e}{K_r} + \frac{1 - n_e}{K_l} \tag{2}$$

in the series case, where

$$n_e = \frac{n_t - n_l}{n_r - n_l} \tag{3}$$

is a function of the porosities (n_t: soil mixture, n_r: reconstituted soil, n_l: lumps) [10].

Assuming the soil structure as a random distribution of the parallel and series cases at different orientations, a generalised equation for the homogenised mixture may be formulated as:

$$\log K = n_e \log K_r + (1 - n_e) \log K_l \tag{4}$$

The homogenised shear stiffness can be obtained by a similar derivation [10,12].

The outlined approach was validated by laboratory experiments and numerical simulations. The numerical model comprised a soil element filled with a certain volume fraction of the lumps embedded in the reconstituted soil (Fig. 8) under isotropic and triaxial shear loading, respectively.

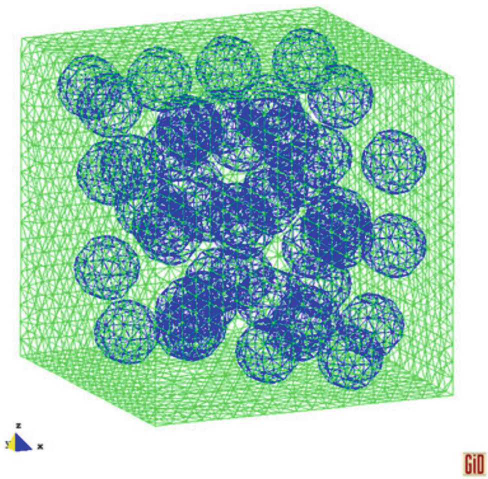

Fig. 8. Numerical model for the validation of the homogenisation method [8].

The lumps are often in an overconsolidated state with respect to low overburden pressures. Standard elastoplastic and hypoplastic models usually overestimate the shear strength at the low effective stress range. Thus, a realistic limit stress condition is needed in the constitutive description of the lumps. A nonlinear Hvorslev surface (see Fig. 5 in Sect. 2) helps to improve numerical predictions of the mechanical behaviour for the lumpy soils [7,14].

5 Lumpy Soil During Consolidation

The consolidation process of a lumpy soil includes a simultaneous consolidation of both (fully saturated) phases, the lumps and the reconstituted soil. A continuous exchange of water between the lumps and the reconstituted soil in the macrovoids takes place. The proposed model is based on two simplifications.

Firstly, there are no direct contacts between the lumps, i.e. the lumps are floating in the reconstituted soil. Secondly, a further disintegration of the lumps is negligible. Consequently, there is no exchange of the solid phase of the lumps into the reconstituted soil. The model enables to follow the non-uniform stress and strain distribution of both phases accompanied by a corresponding evolution of the porosities in time. The excess pore water pressure dissipation in the reconstituted soil is more rapid than in the lumps due to its higher permeability. As a result, there is a transfer of fluid from the lumps to the reconstituted soil, which accelerates the whole consolidation process. A good agreement between laboratory experiments and the model predictions of the compression behaviour (Fig. 9) and of the consolidation times (Fig. 10) could be shown [15].

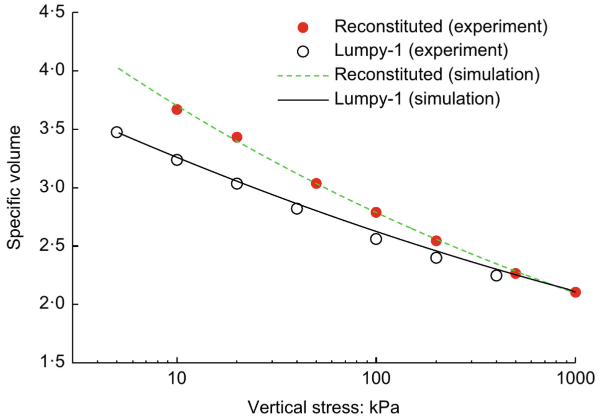

Fig. 9. Experiments and simulations of the compression behaviour of a lumpy soil during consolidation [15].

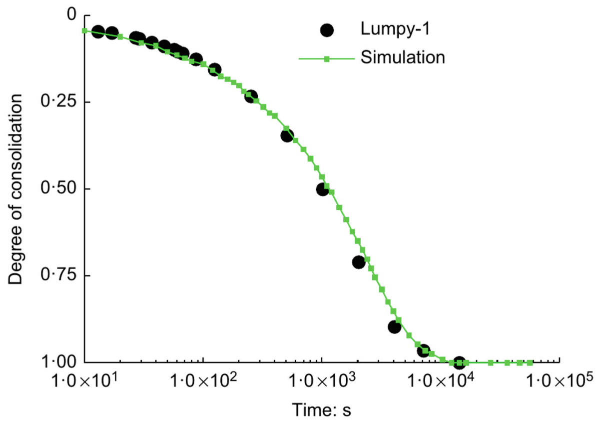

Fig. 10. Measured and calculated consolidation curve for the stress increment between $\sigma_i' = 10\,\text{kPa}$ and $\sigma_{i+1}' = 20\,\text{kPa}$ [15].

6 Concluding Remarks

The material description of multiporous lumpy soils is a challenge for the constitutive modelling. It has been shown that a hierarchical approach can be used for this purpose. A homogenisation model can combine the contributions of the lumps (composed of an overconsolidated soil) and of the reconstituted soil to the overall behaviour. If lumps are floating in the reconstituted soil, a consolidation model can well capture the time evolution of the compressibility.

In spite of a high complexity of the consolidation model [15], many relevant features of dumped lumpy soils are still missing. The following effects should be included if a general model is required for realistic field predictions:

- A part of the lumps can create a quasi-skeleton with voids filled by the reconstituted soil.
- A solid phase of the lumps can be gradually transferred to the reconstituted soil (weathering).
- Air phase is added with focus on the partial saturation of the interlump voids and on the initial suction within the lumps.

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