Conditions for Suffosive Erosion Phemomena in Soils – Concept and Approach –

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Summary. Variances in flow conditions in the subsoil induced by e.g. climatic change or anthropogenic hazard have a potential impact on the activation of erosion processes. Suffosion is one special kind of an erosion process where fines inside the grain structure are vulnerable to be washed out. This article presents a concept that combines various approaches with the aim of understanding transport and clogging phenomena within grain structure. The concept is based upon modelling of idealized grain structures, micro-CT analysis of soil specimen, and percolation theory. The goal of this interdisciplinary approach is a geometric suffosion criterion.

Key words: pore, pore throat, constriction sizes, CT-Scan, modelling

1 Introduction

The vulnerability of river basins as referring to extreme flood events has increased over the past years as a consequence of climatic changes and/or egineering projects. One of the negative results is that any change in flow conditions in river basin scale is a potential impact for erosion processes in subsurface. One kind of such particle displacement is the internal erosion. Internal erosion of soil structures induced by seepage forces is also an evident problem for the stability of retaining structures. During groundwater flow fines in the grain skeleton can be displaced by seepage forces. This kind of erosion where the displacement of fines in the grain skeleton is taking place is called suffosion.

The prototypic application at a side–dam of the Upper-Rhine river revealed that with the currently available criteria to assess suffosion a quantitative statement about the vulnerability of material transport is mostly not possible because of limitations concerning the degree of uniformity or the material itself [12]. Only soils without any cohesive fines can be analysed. The criteria are not transferable without limitation and uncertainty [12]. It is unclear whether the available criteria over or underestimates the problem. The numerous criteria are based mostly on experimental studies in specific soils and under certain boundary conditions.

Novel criteria that remedy the shortcomings of existing approaches could be a way to assess the vulnerability of suffosion. A research project to develop new criteria and laboratory tests concerning this topic is the national research project "Conditions of suffosive erosion phenomena in soils".

2 Overview

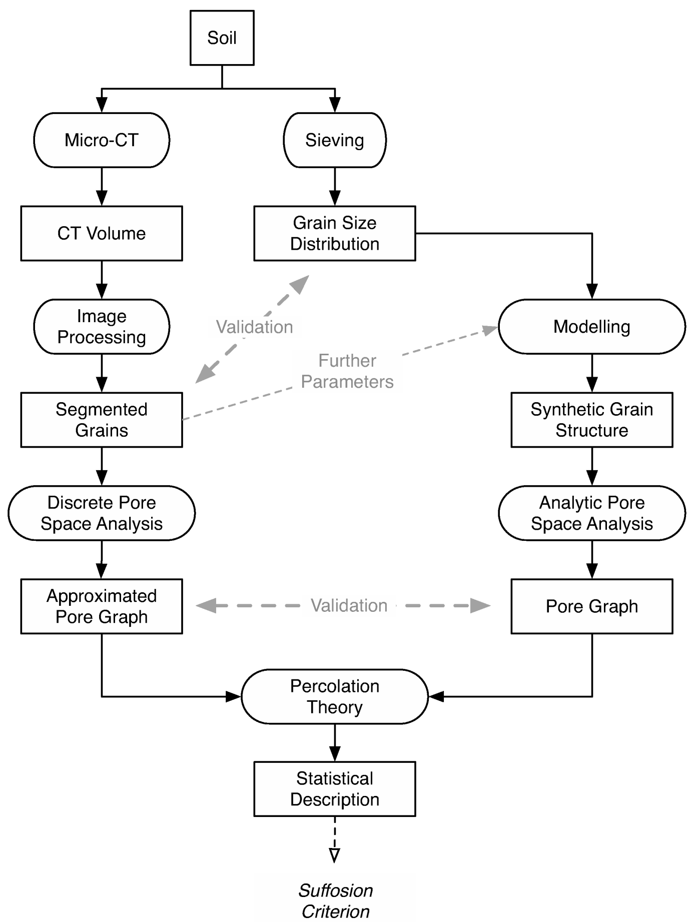

Fig. 1. Overview of the combination of methods that will lead to the suffosion criterion.

We aim at studying suffosion processes in mesoscopic scale, based on the pore structure of suffosive soils. The pore structure is needed to be able to describe the processes in microscale. This is realised by two different approaches to describe the pore structure. Figure 1 illustrates the methods that we propose. One approach uses sieving to measure a particle size distribution, which is input to modelling synthetic particle structures. The second approach builds upon micro–CT and image processing to analyse the three-dimensional geometric situation in soil specimens. In both cases the parameters of the pore structure which are relevant for filtration processes are computed and used for simulation of transport processes as well as the conditions of clogging with percolation models. A systematic analysis of the correltion of grain size data and suffosion potential will allow to assess a geometric suffosion criterion. The two approaches are validated by comparing intermediate results. The results of image processing could provide further parameters for modelling, which is not yet the case.

3 Modelling Grain Structure Using Sphere Packing

The first approach is the realisation of numeric models to investigate specific parameters of the grain and pore structure. This approach models the grain structure as spherical particles. The input parameters are particle number distributions as well as overall porosity. The model of grain structure is created by means of an algorithm having a combined formulation between geometric criteria on gravity and a stochastic-heuristic approach. Subsequently we derive the immobile grain structure from the modelled sphere packing. This is necessary as we use parts of realistic grain-size distributions for modelling and thus small particles might be locked inside pore spaces. However, as these are not required for the stability of the structure, they have to be erased before further considerations.

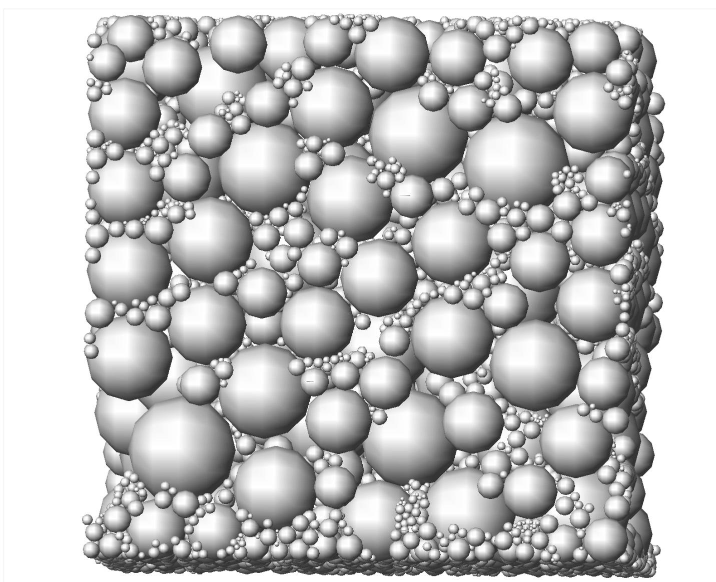

Fig. 2. Exampel of a modelled grain structure.

The obtained models are evaluated regarding their pore structure, as described in Section 5. The details of the method are described in a separate paper [7].

4 Analysing Grain Structure Using Micro-CT

The second approach is based on image processing methods applied to high resolution computed tomography images, so called micro–CT, of real soil specimens and artificial glass sphere structures. The image processing methods build upon and extend the visualisation software Amira [15].

Artificial Soils

We developed appropriate preparation methods of gradated soils (artificial soils) as a basis for micro-CT scans in order to generate three–dimensional datasets of the spatial distribution of the linear attenuation coefficient of the absorbed X-ray radiation. The resulting images represent density differences of the soil structure. The 3D datasets will provide the basis for the visualisation and analysis of the micromorphology of the artificial soils. The soil structure and the pore system of suffosive soils are both essential to the understanding of suffosion. Artificial soil samples whose grain size distribution is taken from a typical fluviatile soil of the Upper–Rhine river area where used as well as mixtures of glass sphere packings in order to prepare the test specimen. The samples are embedded in epoxy resin and cut to an appropriate size. The resolution of micro–CT is limited by the size of the specimen. Larger specimen cause a lower resolution, because only a fixed number of image elements is available to cover the full extent of the specimen. The size of the specimens is to be adapted to reach at least 30 μm resolution.

The particle structure is analysed by the following image processing pipeline. In a first step the particle structure is segmented as a whole by thresholding the data. In further steps, the particles are extracted and identified. The results describe the particle structure by the position, diameter and volume of each extracted particle. Besides quantification, this also provides the possibility to visualise the particle structure. Details are discussed in a separate paper [5].

Visualisation of grain mobilisation

The development of a method to detect the relocation of grains in gradated soils using column experiments is included in the study of artificial soils. This is aimed to derive additional features of suffosive soils and visualise the transport of fines taking into account packing e.g. density, porosity, tortuosity by CT scans before and after the column experiments. A 6×6 cm section of these columns (diameter 6 cm, height 32 cm) were scanned resulting in amount of approximately 1900 2D images. For certain grain size fractions coating of grains or usage of grains with different density was applied to improve the visualisation of the mobile particles. It is intended to derive boundary conditions of transient processes phenomenon in gradated soils by comparing image data.

5 Analysing Pore Structure

Starting from the particle structure, either modelled by sphere packing or computed from micro-CT data, the pore structure can be analysed. The pore space is obtained as the complement of particle structure. For further analysis, the pore structure will be represented as a pore graph. The vertices of the pore graph describe the pore centers and its edges describe possible paths to neighboring pores. The size of the largest particle that can freely move between the two pores connected by the edge is associated with each edge.

As described in a separate article [7], we can compute the pore graph in two different ways. Starting from the synthetic grain structure, represented as spheres, we can apply analytical methods. Alternatively, methods from discrete geometry can be used to compute a discrete approximation of the pore graph as a voxel object. Although the discrete method is less accurate for the synthetic grain structure, it has the advantage that it can be extended to grain structures computed from micro-CT. Pore graphs, so far, have be computed for small test cases. We are confident that the method can be extended to be applicable to larger pore structures.

6 Percolation Theory

A modern approach to comprehend flow and transport mechanisms inside a pore structure is the percolation theory which is a branch of probability theory dealing with properties of random media [1]. Broadbent and Hammersley can be named as originators for the use of percolation theory to study fluids in a maze [4]. Percolation theory is used in several disciplines dealing with complex structures like petrophysics, hydrology, chemistry and statistical physics. Hence there were published several reviews to percolation theory in general (e.g. [3, 16]) and particular in relationship to porous media (e.g. [2, 6, 8] and [10]). Percolation theory deals with three kinds of models namely bond, site and continuum percolation models. Schuler was the first geotechnical engineer who used a very simple percolation model to simulate the penetration length into a filter [9]. The use of percolation theory to describe, phenomenologically, suffosion processes in any particle structure was primarily adopted by Semar and Witt [11, 13].

The huge advantage of percolation models to previous investigations concerning geometrical suffosion criteria is that a transformation of a known 3D pore structure, very close to the reality, is possible. This allows detailed statistical analysis of local and global transport processes inside the pore structure. The rearrangement and transportation of particles can be simulated. To analyse disordered and complex systems the percolation theory is one of the most simple modelling methods. The results have a minimum of statistical dependencies. The disadvantage is that exact solutions do not exist for d–dimensional ($d \geq 3$) lattices [16]. The results are therefore fom stochastical nature.

The aim of the research is to develope a percolation model that describes the rearrangement of fines inside the grain structure adaquately. Therefore it is necessary to get as much information as possible to describe the 3D pore structure correctly. The analysis of pore structure described in the previous sections provides appropriate input parameters. The kind of lattice respectively the type of the percolation model to be used is always a question of homogeneity, uncertainty of input parameters, complexitivity of the model, CPU-Time and reproducibility of results. Details are discussed in a separate article to this workshop [14].

7 Towards a Suffosion Criterion

The statistical results from the percolation models, derived from a Representative Element Volume, are the basic principle to the transformtion into a geometrical suffosion criterion. The definiton of limit state condtitions and the derivation of a geometrical suffosion criterion demand a systematic variation analysis. Based on literature study and experiences it is known that the percentage of grain matrix filling in the specimen and the gradient along the grain size distribution are indices for the vulnerability to suffosion. A univariat statistical analysis with state of the art emprical limit state conditions as input parameters in the steps i) relative density DR and ii) type of grain size distribution (e. g. gap or well graded) will be done. The transport and clogging of particles can be conceived only as a stochastic process. Therefore, a limit state definiton on the basis of the statistical analysis is necessary. Such statistical parameters can be the probability of mobilisation of a specific particle diameter as well as a quantile of the constriction size distibution. The definition of useful statistical indices is part of the research. The correlation between the statistical indices and indirect geotechnical parameters (e.g. grain size distribution or relative density) lead to a transformation into a suffosion criterion. A purposeful criterion could be e.g. the relative density dependent critical inclination of the grain size distribution in the relevant fractions (secant–criterion, heterogeneity of the grain size distribution or tangent–criterion), a criterion with affinity to a limit state grain size distribution or simply a critical relationship of fractile diameters (e. g. $\frac{d_x}{d_{x/2}} \leq C(\rho_d)$) which quantitatively describe the vulnerability to suffosion. This probable simple grain size criteria can be derivated by a transformation of emprical criteria. Hence up to now, as shown in [12], there is no physical explanation.

8 Conclusions and Outlook

Determining the three-dimensional pore structure is necessary to analyse the thread of particle movement locally and globally as a reason of suffosion correctly. The approaches based on image processing methods applied to micro-CT images and modelling of particle packing is promising. The limitation of pore analysis of two-dimensional slices will overestimate the mobility, because only a mean pore space distribution can be determined.

The transformation of the three-dimensional pore structure into a percolation model is possible. First general statements can already be made with uncorrelated bond percolation models. An adaption into a correlated percolation model, where the allocation of the pore structure can be realized closer to reality, is part of ongoing research. The influence of the finite size effect can be done in advance so that an extrapolation to every macroscopic homogeneous soil is possible.

Although the presented work is still in progress, the various approaches start fitting together, yet validation and integration is to be done. First results indicate that the particle distribution computed from micro-CT matches the particle distribution measured by sieving. This needs to be confirmed by a comprehensive study of more soil specimens. Analysing the pore space is already possible for small test cases. Our proposed methods, however, need to be scaled to larger data sets.

9 Acknowledgement

The authors thank the German Research Foundation (DFG) for supporting the research project "Conditions of suffosive erosion phenomena in soil".

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